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# SOIL SCIENCE

Editor-in-Chief  
JACOB G. LIPMAN

Associate Editor  
HERMINIE BROEDEL KITCHEN

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## SOIL SCIENCE



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JULY - DECEMBER, 1929

RUTGERS UNIVERSITY  
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# THE CHEMICAL COMPOSITION OF FLORIDA EVERGLADES PEAT SOILS, WITH SPECIAL REFERENCE TO THEIR INORGANIC CONSTITUENTS

HARALD EDWIN HAMMAR<sup>1</sup>

*University of Florida*

Received for publication March 1, 1929

The Everglades of Florida have, for the past quarter-century, been a topic of much discussion. Large sums of money have been appropriated by the state and national governments for draining and reclaiming this body of organic soils for agricultural purposes. Several drainage canals have been dug, and a branch experiment station has been established by the state for the purpose of studying the problems presented by this vast area.

The Everglades proper occupy the greater portion of south Florida, forming one of the largest bodies of organic soils in the world. They extend from Lake Okeechobee on the north to the Gulf of Mexico on the south, having a length of nearly 100 miles and a maximum width of 50 miles. They have a total area of 7,567 square miles, or 4,843,184 acres of soil material varying from a depth of 8 to 10 feet at Lake Okeechobee to almost nothing at the outer limits. The average depth is about 6 to 8 feet.

Specific information concerning this body of soils is rather limited. The native vegetation and field observations indicate that they are quite different, varying from a state of extremely high natural fertility in the custard apple area, to that of a very low fertility in the saw grass area. The present investigation was undertaken to determine the possible correlation between the natural fertility of these soils and certain chemical properties.

No attempt is made to give a complete review of the literature dealing with the Florida Everglades soils; however, some of the outstanding contributions seem worthy of mention.

Rose has reported a number of chemical analyses of Florida muck and peat soils, including many samples from the Everglades area. The results of his work are given in the Florida state chemist's annual reports for 1912 (10); 1914, 1919, 1920 and 1922 (11). His analyses of muck and peat soils averaged 3.10 per cent ammonia, 0.18 per cent phosphoric acid, and 0.08 per cent potash.

Miller (8), reported a comparison of the chemical properties of saw grass peat with those of the plant from which it was derived, namely saw grass (*Cladium effusum*). He concluded from his results that *seven parts* of saw

<sup>1</sup>The writer wishes to acknowledge the aid and helpful suggestions of Dr. O. C. Bryan of the University of Florida, under whose supervision this work was carried on.

grass were required to produce *one part* of peat, assuming that no silicon was lost in the transformation. On this assumption, 12.2 per cent iron and aluminum, 24 per cent lime, 41 per cent magnesium, 96 per cent potash, 84 per cent soda, 70 per cent phosphorus, and 35 per cent nitrogen were lost during the transformation process.

Waksman (12, 13), reported from a number of decomposition studies on the Florida Everglades soils, that the undrained fibrous peat (saw grass) was high in cellulose (5.6 per cent) whereas the well-drained material (custard apple soil) was free of cellulose.

Forsyth (6), made a biological study of some of the Everglades soils, and concluded that the area known as custard apple soils represented drifted in material to a large extent, whereas the saw grass soils represented a gradual accumulation of plants in place.

Baldwin and Hawker (2), made a survey of a strip of the Florida Everglades soils, beginning on the east side and extending inland to Lake Okeechobee. They described the different soils as peat, peaty muck, and muck, the native vegetation of which is saw grass, elderberry, and custard apple, respectively.

#### EXPERIMENTAL

##### *Soils used*

The soils used in this investigation were classified according to the vegetation found growing on them, as custard apple, elderberry, and saw grass. The greater part of the area of custard apple soil consists of a rim along the southeastern shore of Lake Okeechobee; and the elderberry area forms a belt behind that of the custard apple; whereas the saw grass area lies further from the lake and comprises the greater part of the Everglades proper. Typical soils for each area were selected according to the native vegetation.

The location from which the soils were obtained is given in table 1 and figure 1. Because of the convenience in travel the first four soils of each type were secured near (within 75 to 100 feet) the four main drainage canals; namely, Miami, North New River, Hillsborough, and West Palm Beach. The other samples were secured from representative areas.

##### *Method of collecting samples*

The soil samples were secured with an ordinary post-hole digger. The surface vegetation was cleared away and representative samples weighing about two pounds were taken from the first, second, third, fourth, and fifth foot depths, placed in small bags and taken to the laboratory and allowed to air-dry, after which they were ground and stored in quart Mason Jars. Samples were taken from eight typical areas of each of the three types of soil, thus making a total of 120 samples. The surface foot soils were ground to pass an 80-mesh sieve for chemical analyses and specific gravity determinations, but the samples for acidity and ash determinations were not ground.

## CHEMICAL COMPOSITION OF THE FLORIDA EVERGLADES SOILS

Standard methods were used for all chemical procedures except that the potash was determined from the ignited soil, and duplicates were made on each determination. The methods used in this study are described by Emerson (5) and Mahin (7).

The insoluble residue was determined by digesting the ash in hydrochloric and nitric acid, after which the residue was washed, ignited, and weighed.

TABLE 1  
*Location of areas from which samples were obtained*

NUMBER	SAMPLE	LOCATION
1	Custard apple	North New River Canal at South Bay, $\frac{1}{2}$ mile from Lake Okeechobee
2	Custard apple	Hillsborough Canal at "Chosen"
3	Custard apple	West Palm Beach Canal at Canal Point
4	Custard apple	Miami Canal at Miami Locks $\frac{1}{2}$ mile from Lake Okeechobee
5	Custard apple	North of Hart's Farm, near South Bay
6	Custard apple	Hart's Farm, between Bell Glade and South Bay. Virgin soil*
7	Custard apple	Between South Bay and Ritta
8	Custard apple	Between South Bay and Belle Glade
9	Elderberry	North New River Canal, $1\frac{1}{2}$ miles south of Lake Okeechobee
10	Elderberry	Hillsborough Canal, 3 miles from Lake Okeechobee
11	Elderberry	West Palm Beach Canal at Ertermara Sugar Farm
12	Elderberry	Miami Canal at Ritta. Virgin soil
13	Elderberry	Everglades Experiment Station, Grass Garden. Cult. 2 years
14	Elderberry	Two Miles N. E. Belle Glade, $\frac{1}{2}$ mile into Elderberry area
15	Elderberry	Hillsborough Canal, 3 miles from Lake Okeechobee
16	Elderberry	Between Belle Glade and Everglades Experiment Station
17	Saw grass	North New River Canal at Okeelanta, 4 miles S. Lake Okeechobee
18	Saw grass	Hillsborough Canal at Everglades Experiment Station
19	Saw grass	West Palm Beach Canal—Connor's Highway between Canal Point and 20 Mile Bend. 3 miles West of First Gate.
20	Saw grass	Miami Canal at Ritta. Virgin soil
21	Saw grass	Geerwarth. Capt. Codd's Place. Cultivated several years
22	Saw grass	Hillsborough Canal at Six Mile Bridge.
23	Saw grass	Glade View. Between Belle Glade and 20 Mile Bend
24	Saw grass	$\frac{1}{2}$ mile North of Everglades Experiment Station

\* All soils had been cultivated some unless otherwise indicated.

The insoluble residue (as  $\text{SiO}_2$ ), N, CaO, MgO,  $\text{Fe}_2\text{O}_3$ ,  $\text{K}_2\text{O}$ , and  $\text{Al}_2\text{O}_3$ , as found in the different soils, are given in table 2.

The chemical analyses shown in table 2 support the assumption that the custard apple and saw grass soils are two distinct types. This cannot be said, however, of the elderberry soil, which in general appearance, productivity, and location would seem to be a distinct intermediate type.

The chemical analysis of soil 15 (herein classed as elderberry) places it

definitely in the class of the custard apple soils, whereas that of the elderberry soils 11, 12, 13, 14, and 16 is practically identical with the saw grass soils. A truly intermediate type is apparently represented in soils 9 and 10.

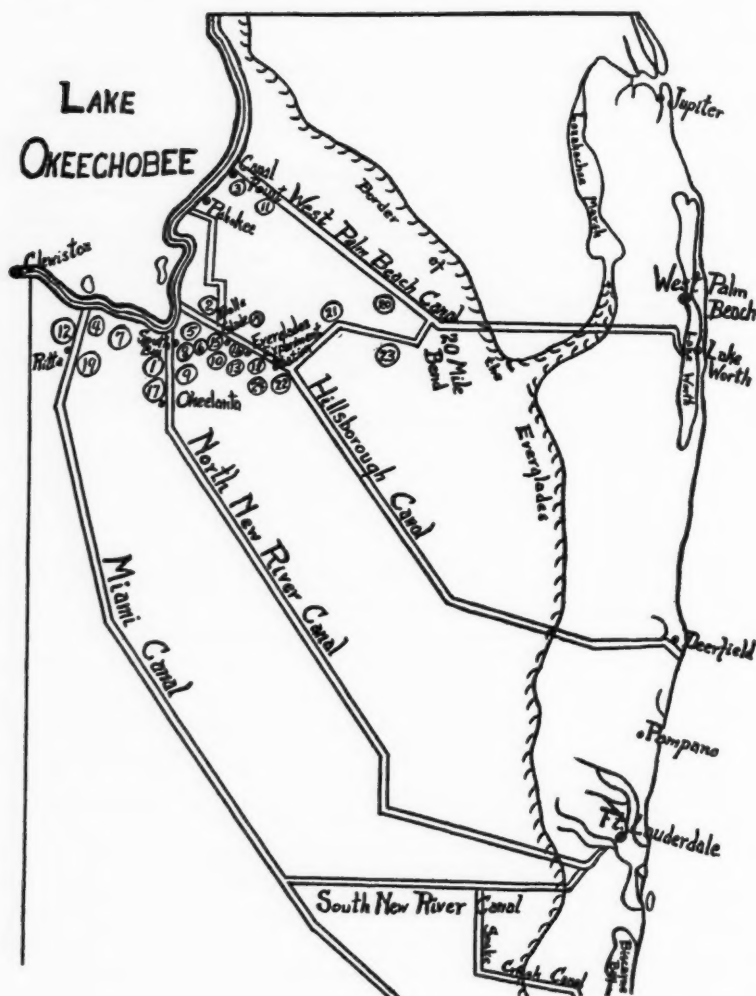


FIG. 1. LOCATION OF SOILS USED IN THIS INVESTIGATION

The custard apple and saw grass soils will be discussed in terms of averages, but obviously averages of the chemical data of the elderberry soils would be meaningless, and will not be considered. The reader can easily see by examin-



ing the various tables that soils 9 and 10 are about half-way between the two extreme types in all physical and chemical comparisons attempted.

It will be noted that the nitrogen in the custard apple soil (1.47 per cent) is very much lower than that in either the elderberry or the saw grass soils (2.79 per cent).

TABLE 2  
*Chemical analyses of some Everglades soils*  
(Samples from surface foot of soil, oven-dry basis)

NUMBER	SAMPLE	SiO <sub>2</sub>	N	CaO	MgO	Fe <sub>2</sub> O <sub>3</sub>	P <sub>2</sub> O <sub>5</sub>	K <sub>2</sub> O	Al <sub>2</sub> O <sub>3</sub>
		per cent	per cent	per cent	per cent	per cent	per cent	per cent	per cent
1	Custard apple	36.02	1.315	4.500	0.0748	4.376	0.5070	0.031	4.216
2	Custard apple	40.14	1.234	4.060	0.1110	5.354	0.4190	0.028	5.773
3	Custard apple	36.11	1.798	5.660	0.0905	3.547	0.6160	0.052	3.128
4	Custard apple	27.06	1.891	5.140	0.0966	4.596	0.6040	0.095	3.461
5	Custard apple	25.03	1.508	3.008	0.0845	5.427	0.4623	0.036	2.861
6	Custard apple	36.16	1.503	2.750	0.0543	5.330	0.8022	0.050	5.068
7	Custard apple	42.11	1.411	2.529	0.1330	4.830	0.1851	0.039	5.535
8	Custard apple	43.91	1.100	2.868	0.0604	6.826	0.2160	0.049	5.578
Average custard apple...		35.82	1.470	3.814	0.0881	5.036	0.4764	0.048	5.077
9	Elderberry	16.90	2.398	2.640	0.1930	2.046	0.4610	0.087	1.297
10	Elderberry	18.99	2.406	4.860	0.0869	2.416	0.3860	0.031	2.055
11	Elderberry	1.58	2.726	6.860	0.2530	0.539	0.4390	0.096	0.182
12	Elderberry	1.46	3.051	6.720	0.0483	0.833	0.5940	0.041	0.000
13	Elderberry	2.28	2.612	5.317	0.1270	2.036	0.2314	0.032	0.000
14	Elderberry	5.55	2.872	5.387	0.0664	2.201	0.3394	0.044	0.060
15	Elderberry	29.40	2.094	3.218	0.1150	2.537	0.4163	0.054	2.597
16	Elderberry	2.86	3.001	6.996	0.1150	1.836	0.4623	0.047	0.002
Average elderberry.....		9.87	2.645	5.250	0.1256	1.805	0.4165	0.054	0.777
17	Saw grass	7.14	2.683	2.930	0.1330	1.357	0.7860	0.079	0.734
18	Saw grass	3.66	2.586	10.150	0.0814	1.171	0.5040	0.011	0.558
19	Saw grass	4.89	2.834	2.510	0.1570	1.164	0.6860	0.043	0.000
20	Saw grass	2.24	3.020	7.320	0.0757	0.932	0.4460	0.033	0.000
21	Saw grass	Lost	3.231	3.988	0.1210	0.539	0.3701	0.027	0.000
22	Saw grass	1.96	2.917	5.037	0.0604	0.140	0.2005	0.040	0.559
23	Saw grass	4.40	2.513	3.710	0.1090	1.078	0.2005	0.034	0.142
24	Saw grass	4.97	2.569	6.017	0.0724	1.696	0.4220	0.028	0.422
Average saw grass.....		4.18	2.794	5.208	0.1012	1.010	0.4156	0.037	0.302

*Note:* Soils 11, 12, 13, 14, and 16, although placed in the elderberry group because of general appearance, native vegetation, and productivity, are chemically nearly identical with the saw grass soil. Likewise, soil 15 chemically resembles the custard apple muck.

The content of iron, aluminum, and insoluble residue (silica) as noted in table 2, is much higher in the custard apple soil than in the saw grass soils. Calcium and magnesium average a little higher in the saw grass soils than in the custard apple, but there is so much variation that averages mean little.

It is interesting to note that the custard apple soils contain about 16 times as much aluminum and 5 times as much iron as do the saw grass soils. The content of phosphorus does not vary to any marked degree from one type to another. However, there is a considerable variation within the custard apple soil. The content of potash was also variable within the soil type but the average amounts were not very different from type to type.

#### *Reaction*

The reaction of the soils was determined according to the Truog method which seemed to give a better estimate of the total acid present than did a measure of the hydrogen-ion concentration. The average pH value of the saw grass soils was 6.7; these soils contain some free calcium carbonate.

The surface soil in practically all instances was more acid than the subsoil. The custard apple soil was strongly acid on the surface, and decreased in acidity with depth, whereas the elderberry and saw grass soils were only slightly acid on the surface and decreased to neutrality at the lower depths.

#### PHYSICAL PROPERTIES OF THE EVERGLADES SOILS

##### *Fiber content and color*

Plate 1 shows the relative amount of undecomposed plant materials (fiber) in the three soils. It will be seen that the original plant material is rather abundant in the saw grass soils, with practically no visible amounts in the custard apple soils. The elderberry soil is intermediate. The custard apple soil was usually black, whereas the other two soils were brown.

##### *Specific gravity*

The specific gravity of the surface soils is given in table 4. It will be noted that the specific gravity of the custard apple soils (1.6) is much greater than that of the saw grass soils (1.27).

##### *Structure*

The custard apple soils were hard and granular when dry, with very little change upon increase of depth, whereas the elderberry and saw grass soils were comparatively soft and loose. The custard apple soil was also somewhat plastic when wet, in contrast to the other two types.

##### *Water-holding capacity*

The hygroscopic and capillary water capacities of the different soils were determined under laboratory conditions, and the results are given in table 4. It will be noted that, in general, the custard apple soils have a somewhat lower content of hygroscopic and much lower content of capillary water than do the other two soils. This is no doubt due to the difference in organic matter present. The saw grass soils had an average of 382.88 per cent capillary and hygroscopic water combined, and the custard apple 223.81 per cent.

*Organic matter and ash content*

The ash content and loss on ignition of the different soils are given in tables 3 and 4. The custard apple soils averaged 55.48 per cent ash and that of the saw grass soils 12.91 per cent. The loss on ignition was assumed to be practically the same as organic matter. It is worthy of note that the ash content

TABLE 3  
*Loss on ignition of some Everglades soils*  
(Percentage oven-dry basis)

NUMBER	SAMPLE	FIRST FOOT	AVERAGE FIRST FOOT	SECOND FOOT	AVERAGE SECOND FOOT	THIRD FOOT	AVERAGE THIRD FOOT	FOURTH FOOT	AVERAGE FOURTH FOOT	FIFTH FOOT	AVERAGE FIFTH FOOT
1	Custard apple	42.59	....	45.88	....	57.19	....	72.23	....	87.60	....
2	Custard apple	34.88	....	35.92	....	36.38	....	28.81	....	20.00	....
3	Custard apple	48.26	....	44.09	....	34.77	....	29.54	....	32.63	....
4	Custard apple	56.69	44.52	41.40	44.34	42.66	44.84	46.60	46.34	....	47.90
5	Custard apple	47.14	....	50.42	....	51.59	....	31.30	....	32.23	....
6	Custard apple	46.36	....	41.80	....	53.98	....	61.69	....	33.59	....
7	Custard apple	43.57	....	52.42	....	40.31	....	54.62	....	82.58	....
8	Custard apple	36.70	....	42.02	....	41.80	....	45.92	....	46.69	....
9	Elderberry	70.58	....	69.74	....	68.80	....	75.69	....	86.35	....
10	Elderberry	68.08	....	51.10	....	57.19	....	....	....	....	....
11	Elderberry	89.52	....	90.54	....	85.91	....	72.06	....	65.68	....
12	Elderberry	89.94	80.15	91.09	74.84	90.59	77.65	90.15	83.43	91.27	81.36
13	Elderberry	88.96	....	88.97	....	88.55	....	87.77	....	88.36	....
14	Elderberry	84.11	....	80.10	....	90.68	....	84.78	....	68.29	....
15	Elderberry	61.63	....	45.07	....	51.78	....	....	....	....	....
16	Elderberry	88.34	....	82.06	....	87.70	....	90.10	....	88.25	....
17	Saw grass	81.38	....	90.53	....	91.00	....	63.19	....	86.44	....
18	Saw grass	82.33	....	65.63	....	57.08	....	68.99	....	68.05	....
19	Saw grass	86.08	....	91.81	....	90.62	....	92.69	....	93.73	....
20	Saw grass	87.93	87.09	90.51	86.58	90.72	85.23	91.01	83.30	93.33	86.44
21	Saw grass	90.51	....	93.15	....	....	....	....	....	....	....
22	Saw grass	89.39	....	81.70	....	87.40	....	87.41	....	89.63	....
23	Saw grass	90.82	....	91.67	....	93.10	....	95.12	....	94.98	....
24	Saw grass	88.25	....	87.68	....	86.71	....	84.70	....	78.94	....

at different depths in the same soil type was quite variable and irregular. Seven soils showed a decrease of ash with depth whereas five others showed an increase with depth. Of the remaining twelve soils, ten were irregular in their variation and two (with about 10 per cent ash) had about the same percentage at all depths.

## DISCUSSION

From the chemical and physical characteristics of the custard apple soils, it would seem that these soils were formed either from the drifting in of ex-

TABLE 4  
*Specific gravity, hygroscopic and capillary water, loss on ignition, and ash content of some Everglades soils*

(Samples from surface foot, per cent oven-dry basis)

NUMBER	SAMPLE	SPECIFIC GRAVITY	HYGROSCOPIC AND CAPILLARY WATER		LOSS ON IGNITION	ASH CONTENT
			Hygroscopic	Capillary		
			<i>per cent</i>	<i>per cent</i>	<i>per cent</i>	<i>per cent</i>
1	Custard apple	1.62	10.51	207.96	42.59	57.41
2	Custard apple	1.60	12.32	.....	34.88	65.12
3	Custard apple	1.49	10.84	241.90	48.26	51.74
4	Custard apple	1.50	11.17	227.72	56.69	43.31
5	Custard apple	1.62	13.83	.....	47.14	52.86
6	Custard apple	1.63	14.06	216.32*	46.36	53.64
7	Custard apple	1.65	13.06	.....	43.57	56.43
8	Custard apple	1.73	12.40	225.18	36.70	63.30
Average custard apple.....		1.60	12.25	223.81	44.52	55.48
9	Elderberry	1.35	18.03	326.33	70.58	29.42
10	Elderberry	1.32	14.47	366.65	68.08†	31.92
11	Elderberry	1.22	18.28	.....	89.52	10.48
12	Elderberry	1.22	14.20	289.19*	89.94	10.06
13	Elderberry	1.27	16.24	.....	88.96	11.04
14	Elderberry	1.17	15.75	380.14	84.11	15.89
15	Elderberry	1.46	14.44	340.34*	61.63	38.37
16	Elderberry	1.31	15.52	.....	88.34	11.66
Average elderberry.....		1.29	15.85	336.53	80.15	19.85
17	Saw grass	1.23	16.50	410.13	81.38	18.62
18	Saw grass	1.27	18.10	.....	82.33	17.67
19	Saw grass	1.25	14.33	370.86	86.08	13.92
20	Saw grass	1.20	22.36	373.56*	87.93	12.07
21	Saw grass	1.28	16.16	.....	90.51	9.49
22	Saw grass	1.28	16.26	295.76	89.39	10.61
23	Saw grass	1.29	12.05	364.10	90.82	9.18
24	Saw grass	1.34	16.00	.....	88.25	11.75
Average saw grass.....		1.27	16.47	382.88	87.09	12.91

\* Soils nos. X, 26, IX, and XI respectively in order listed—not included in table 1.

† See note under table 2.

traneous materials from the flooded waters of Lake Okeechobee, or represent an advanced stage of decomposition of materials which formed the saw grass soils.

The theory that the custard apple soil represents an advanced stage of decomposition would gain some support from the fact that the percentages of silicon, iron, and aluminum are much higher in these soils, and from the presence of very large amounts of fibrous material in the saw grass soils compared with little or none in the custard apple type. Such a theory, however, gains little support from the fact that there is little difference in the ratio between the organic matter and nitrogen in the two types of soils. The two soils do not differ greatly in the average amounts of phosphorus, potassium, magnesium, and calcium.

The presence of the larger amounts of silicon, aluminum, and iron in the custard apple soils could be explained by assuming that these elements were washed in by over-flow water from Lake Okeechobee. This agrees well with the fact that the custard apple soil is found in a narrow strip parallel to and adjoining the lake shore and is found to be much wider on the southeastern side where the low sand ridge, which practically surrounds the lake, is absent. Forsaith's (6) morphological studies show that the sedimentary soils of which the custard apple soil is a type, contains large amounts of diatoms, which were probably carried in by water.

The saw grass soil was found by Waksman (13) to contain considerable amounts of cellulose (5.22 per cent) whereas the custard apple type was found to be devoid of cellulose. This cannot be attributed to a greater decomposition change in the custard apple soils, since it has not been sufficient to change greatly the ratio of organic matter to nitrogen.

The high content of silicon, aluminum, and iron in the custard apple soils together with the non-fibrous organic matter, having a nitrogen content similar to that of the organic matter of the saw grass soils, indicates strongly that the former are in the main sedimentary in nature.

Although as a whole the custard apple soils appear to be in a slightly advanced stage of decomposition, an examination of the soil profile shows that as a rule there is a brown and fibrous strata, containing a low ash content, within the 5-foot depths. On the other hand a dark plastic layer is often found in the lower depths of the saw grass soil. This zonification would indicate that different strata or layers were formed under different conditions of drainage, and from a different type of material at that period of formation.

Miller (8) and Baldwin and Hawker (2), report an increase in ash content upon increase in depth. It has been previously indicated that the soils herein reported are very irregular in this respect. However, their samples were taken at much greater depth (10 and 11 feet) than those used in this investigation.

The reaction of the soils, seems to indicate that there has been some leaching of carbonates, especially in the custard apple soils. The decrease in acidity upon increase in depth was doubtless due to the presence of calcium carbonate at the lower levels. The calcium content in the lower depth was not determined, but Miller (8) reports more calcium in the subsoil of saw grass peat than in the surface, and attributes it to leaching. It may be that an upward

movement of calcium from the rock beneath accounts for the apparently high content and lower acidity at the lower zones.

The specific gravity and degree of hardness were in proportion to the ash content. The water-holding capacity is not in accord with the results of Wheeler (14), who reports that the water-holding capacity of a peat is 600 per cent. Beattie (3) reports that air-dry peat will absorb eight times its weight in water. These results were probably obtained from different types of material, which would no doubt affect the absorptive power of the soil. Whitson and Walster (15) claim that the water-holding capacity of a peat varies from 201 to 309 per cent. Their results agree very closely with those in this study. The water-holding capacity of the different soils is roughly in proportion to the amount of organic matter present.

The results do not indicate that the poor plant growth on the saw grass soils is due to a deficiency of the usual fertilizer constituents, nitrogen, phosphorus, and potassium. These soils are made productive, however, by the use of small amounts of copper and manganese sulfates (1). The function of these chemicals in this case is not known at present.

#### SUMMARY

Twenty-four representative soils from the Florida Everglades were selected for this study. They were classified according to the native vegetation growing on them; namely, saw grass, elderberry, and custard apple. Eight representative areas to a depth of five feet each, of these three types of soil, were used.

The chemical analyses and specific gravity determinations were made from the surface foot soils only, while the ash and acidity determinations were made on all the soils at the various depths. The results are as follows:

1. The custard apple and saw grass soils were found to represent two chemically distinct types. The results place the former in the class of true *mucks*, and the latter, true *peats*. The results indicate that the custard apple soils are sedimentary in nature, and the saw grass accumulative.
2. The elderberry soil is not so distinct, from this standpoint. Soils 11, 12, 13, 14, and 16, are practically identical in analysis with the saw grass soils, whereas soil 15 would be placed with the custard apple group. Two soils, 9 and 10, are chemically intermediate between the two extreme types.
3. The custard apple and saw grass soils averaged 35.81 per cent, and 4.12 per cent silicon dioxide; 5.077 per cent, and 0.301 per cent aluminum oxide; and 5.036 per cent and 1.010 per cent iron oxide.
4. The custard apple and saw grass soils averaged 1.470 per cent, and 2.784 per cent nitrogen; 0.4764 per cent and 0.4156 per cent phosphorus pentoxide; and 0.048 per cent and 0.037 per cent potassium oxide, in order named.
5. The average calcium oxide content for the custard apple and saw grass soils was 3.814 per cent, and 5.208 per cent respectively, whereas the magnesium oxide content was 0.0881 per cent and 0.0102 per cent respectively.

The reaction of the custard apple soil was acid, whereas elderberry and saw grass soils were

slightly acid to neutral. The acidity decreased upon increase in depth, whereas the calcium and magnesium probably increased.

6. The custard apple and saw grass soils contained 44.52 per cent and 86.37 per cent organic matter; 12.25 per cent and 16.47 per cent hygroscopic water; and 223.81 per cent and 382.88 per cent capillary water respectively.

7. The saw grass and elderberry soils are light brown to dark brown in color, light, loose, and soft; whereas those of the custard apple are black, heavy, granular, and hard.

8. The irregularity of color, fiber, and ash content of the profiles of these soils indicate alternate sedimentation and cumulation of layers or zones in the soil.

9. The custard apple soils have a higher natural fertility than the saw grass soils, but the latter are rendered productive by the use of copper and manganese salts. The poor fertility of the saw grass soil is not due to the absence of the usual fertilizer constituents, nitrogen, phosphorus, and potassium.

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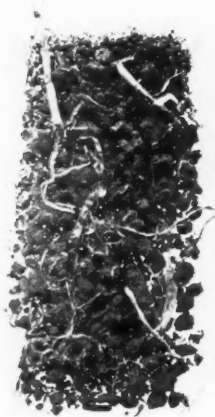
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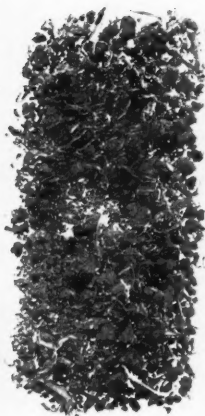
## PLATE 1

## RELATIVE AMOUNTS OF PARENT PLANT MATERIAL IN EVERGLADES SOILS

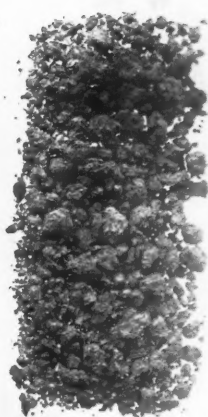
(The custard apple soil contains very little fibrous material, whereas the elderberry and saw grass soils contain relatively high amounts.)



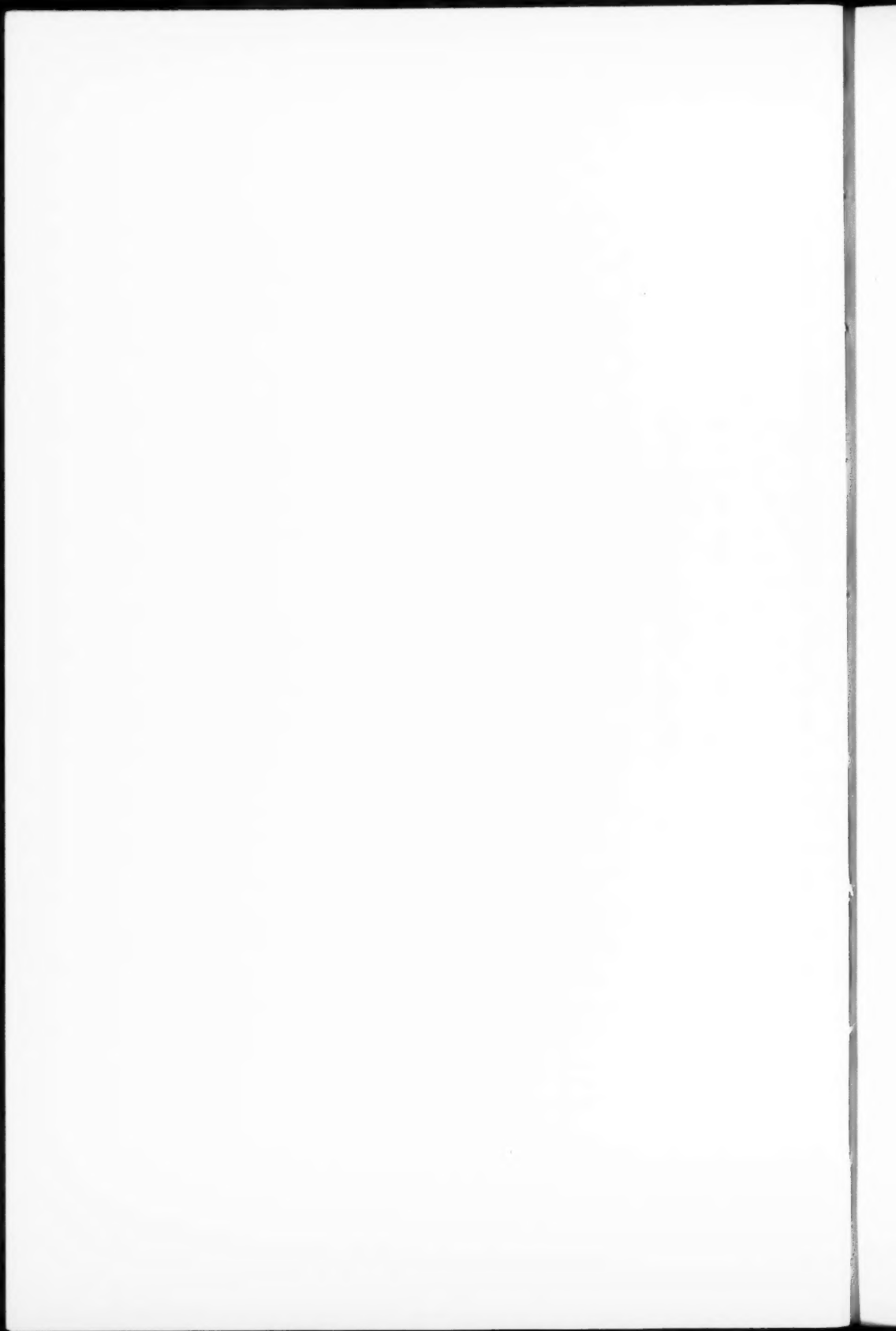
No. 1. Saw Grass



No. 2. Elderberry



No. 3. Custard Apple



## VARIATIONS IN THE CALCIUM AND MAGNESIUM CONTENTS OF PEA PLANTS ON DIFFERENT SOIL TYPES<sup>1</sup>

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Two previous papers (2, 3) contained data showing variations in the calcium and magnesium contents of alfalfa and bean plants when grown on different soil types, and also showing the relationship of these to some properties of the soils. The material presented here is of the same nature in regard to the pea plant and completes the material dealing with the effect of soil type upon certain of the characteristics of three important legumes.

Because of their wide range of adaptability, field peas constitute one of the leading sources of legume forage, and likewise one of the important leguminous crops used widely in farm rotations looking to the maintenance of soil fertility. Because of these facts any information related to variations in the composition of field peas, and causes inducing them, has a practical significance.

A rather comprehensive review of the work which has been done relative to the discussion taken up here was given in the aforesaid papers on alfalfa and beans, obviating any need for such review in this paper. Likewise the plan of the experiment was the same as that followed for beans (3) and the experimental methods were the same as reported in the other two papers. These exceptions should be noted however, that Roselawn soil was not included in the work with peas, reducing the number of soils to six, and also that the period of growth of the peas was prolonged so greatly, probably because of abnormal photoperiodism, that three stages of growth were obtained before budding and no samples were taken at the stage when the fruit was setting on. The variety of peas used was Scotch green field peas.

As in the case of the work reported on beans, a knowledge of the effect of plant growth on the soil characteristics studied here is necessary to an understanding of the other material. For this reason a discussion of these data will be given first.

### EFFECT OF GROWTH OF PEAS UPON CALCIUM AND MAGNESIUM CONTENTS OF SOIL SOLUTIONS AND UPON pH VALUES OF SOILS

Very much the same effect upon the calcium and magnesium contents of the soil solution was produced by the growing pea plants, shown in tables 1 and 2,

<sup>1</sup> Part III of a thesis presented to the graduate committee of Michigan State College in partial fulfillment of the requirements for the degree of doctor of philosophy.

<sup>2</sup> The writer wishes to express his appreciation to Dr. M. M. McCool for his kindly interest and suggestions in the execution of this work.

as was found in the case of growing bean plants (3). Although it is evident that before growth started the amounts of calcium and magnesium present in the several soil solutions varied greatly, by the time the pea plants had reached the mature stage the amounts had been reduced until there was but little difference among the soil types. However, the reduction in the concentration of the two elements in the solutions was not rapid and was very uniform, the soil types maintaining the same order with respect to each other during most

TABLE 1  
*Variations in calcium content of soil solutions growing peas*  
Parts per million of water-free soil

SOIL TYPE	INITIAL CONTENT	STAGES OF GROWTH		
		Content at 3 weeks	Content at 6 weeks	Content at maturity
Plainfield.....	10.60	2.99	4.85	3.02
Kewanee.....	44.70	38.80	21.00	1.60
Onaway.....	24.55	20.95	.....	1.93
Hillsdale.....	14.62	12.81	7.00	1.92
Brookston.....	19.10	8.22	10.12	5.10
Miami.....	30.06	23.35	18.50	3.13

TABLE 2  
*Variations in magnesium content of soil solutions growing peas*  
Parts per million of water-free soil

SOIL TYPE	INITIAL CONTENT	STAGES OF GROWTH			
		Content at 3 weeks	Content at 6 weeks	Content at 8 weeks	Content at maturity
Plainfield.....	4.44	3.18	Trace	0.66	1.90
Kewanee.....	8.88	4.55	4.99	1.87	Trace
Onaway.....	7.45	5.11	.....	1.33	1.55
Hillsdale.....	4.08	2.39	0.98	2.52	1.71
Brookston.....	3.48	0.92	Trace	Trace	Trace
Miami.....	10.2	5.81	1.11	2.05	1.61

of the growth period. It appears that pea plants reduced the calcium content of the soil solution less rapidly, but to a greater degree, than had been found for bean plants, although the effect of the two crops on the magnesium content of the soil solutions was found to be about the same. It thus appears from tables 1 and 2 that in point of concentration of calcium and magnesium in their solution the soils may be considered as decreasing in the order of Kewanee, Onaway, Hillsdale, and Plainfield for the light soils, and of Miami and Brookston for the heavy soils.

## CHANGES INDUCED IN THE HYDROGEN-ION CONCENTRATION OF THE SOILS BY THE GROWTH OF PEA PLANTS

The hydrogen-ion concentration of the soils, represented by the pH values in table 3, appears to have fluctuated considerably during the growth period of the plants. Rather larger variations appeared than can be attributed to other contributory causes, and it is evident that the pH values of the strongly acid soils were raised whereas those of the alkaline or neutral soils were decreased by the growing plants. This was not found true for beans (3) but appears to be in order with the work reported by Arrhenius (1). However, throughout the growth period the soils maintained their relative positions in respect to their hydrogen-ion concentrations and can be considered as in the order given in table 3, where they are grouped into light and heavy soils.

TABLE 3  
*Effect of growth of peas on the pH value of the soil*

SOIL TYPE	INITIAL VALUE	STAGES OF GROWTH				
		Value at 3 weeks	Value at 6 weeks	Value at 8 weeks	Value at bud- ding	Value at ma- turity
	pH	pH	pH	pH	pH	pH
Onaway.....	7.40	7.15	....	7.50	7.14	7.17
Plainfield.....	7.35	7.69	7.40	7.37	6.99	6.95
Hillsdale.....	6.25	6.12	6.18	6.64	6.50	5.96
Kewanee.....	5.10	5.11	5.00	5.80	....	5.85

<i>Heavy soils</i>						
Brookston.....	7.05	7.33	7.01	7.15	....	6.83
Miami.....	5.00	5.18	4.80	5.05	....	5.38

## CALCIUM CONTENT OF GREEN PEA STEMS AND LEAVES AT DIFFERENT STAGES OF GROWTH WHEN GROWN ON DIFFERENT SOIL TYPES

*Stems*

Noticeable differences were found in the calcium content of the stems of green pea plants grown on the different soil types, as is shown in table 4. Generally the stems of plants grown on any one soil were quite uniformly either high or low in calcium in relation to the stems of plants grown on the other soils. But it is readily apparent that the calcium content of the stems did not depend entirely upon the concentration of this element in the soil solution, nor upon either the pH value of the soils or their textures. It does appear however, that all three of these factors may have played a part in controlling the amounts of calcium contained in the stems. Thus, the calcium content was generally high in the stems of plants grown on the heaviest soil types, but always one of the lighter soils produced plants the stems of which were likewise

high in calcium. Also, if only the light textured soils are considered, and if Onaway and Plainfield are recognized as alkaline, and Kewanee and Hillsdale as acid, it becomes apparent that the soils of similar hydrogen-ion concentrations produced pea plants whose stems usually contained calcium in proportion to the amounts present in the soil solutions. This relationship cannot be applied to the Miami and Brookston soils studied.

Considerable variation occurred in the calcium content of the pea stems at different stages of growth, but there was no uniform increase or decrease as the growth period advanced. In the stems of plants grown on four of the soil types, less calcium was present in the green material at maturity than at the beginning of growth, but in the other two samples there was more present.

TABLE 4  
*Calcium content of green pea stems at different stages of growth on different soil types*

SOIL TYPE	STAGE OF GROWTH				
	3 weeks	6 weeks	8 weeks	Budding	Maturity
	per cent	per cent	per cent	per cent	per cent
<i>Light, alkaline soils</i>					
Onaway.....	0.181	.....	0.124	0.140	0.208
Plainfield.....	0.167	0.139	0.157	0.110	0.121
<i>Light, acid soils</i>					
Kewanee.....	0.135	0.173	0.146	.....	0.191
Hillsdale.....	0.144	0.135	0.087	0.102	0.132
<i>Heavy soils</i>					
Miami.....	0.162	0.233	0.168	.....	0.108
Brookston.....	0.174	0.176	0.150	.....	0.128

#### *Leaves*

It is apparent from the data in table 5 that similar variations occurred in the calcium content of the green material of pea leaves as was found in that of the green material of pea stems. Differences of considerable magnitude appeared in the calcium content of the leaves obtained from the different soil types throughout the period of growth, and these became greater toward the close of the growth period.

Although it is evident that the calcium present in the pea leaves did not correspond entirely to the concentration of this element in the soil solutions, when the soils were of similar texture and hydrogen-ion concentration, the amount of calcium contained in the green leaves was higher when the amount contained in the soil solution was high, and vice versa. It is noticeable that



the average percentage of calcium in the leaves grown on alkaline soils was greater than that of the leaves grown on the acid soils, where Brookston and Miami soils are not considered. In these cases the situation was reversed.

Much greater amounts of calcium were present in the mature green pea leaves than in the young leaves and, although not entirely uniform throughout the period of growth, the increase of calcium was generally quite rapid.

Larger amounts of calcium were present in the leaves of peas than in the stems during the entire period of growth and the ratio between the amounts in the two plant parts became much wider toward maturity.

TABLE 5  
*Calcium content of green pea leaves at different stages of growth on different soil types*

SOIL TYPE	STAGE OF GROWTH				
	3 weeks	6 weeks	8 weeks	Budding	Maturity
	per cent	per cent	per cent	per cent	per cent
<i>Light, alkaline soils</i>					
Onaway.....	0.259	.....	0.260	0.462	0.536
Plainfield.....	0.193	0.286	0.285	0.379	0.384
<i>Light, acid soils</i>					
Kewanee.....	0.196	0.359	0.274	0.292	0.418
Hillsdale.....	0.185	0.332	0.254	0.292	0.282
<i>Heavy soils</i>					
Miami.....	0.197	0.384	0.278	.....	0.582
Brookston.....	0.193	0.293	0.336	.....	0.436

CALCIUM CONTENT OF THE EXPRESSED JUICE OF PEA LEAVES AND STEMS AT  
DIFFERENT STAGES OF GROWTH ON THE DIFFERENT SOIL TYPES

*Juice of stems*

Significant differences were found in the amounts of calcium in the expressed juice of pea stems of plants obtained from the different soil types, as is shown in table 6. These data are marked by considerable lack of uniformity among the different soil types, no one type giving stems with juice consistently higher or lower in calcium than any of the other soil types.

The same relationship between the calcium content of the juice and the properties of the soils studied is evident here as was noted in the case of the calcium content of the green tissue of stems, except that variations in texture had less influence than in the other case. But on soils of similar reaction the calcium content of the expressed juice usually varied directly as the concentra-

tion of calcium in the soil solution. Where soil texture and more particularly soil reaction, are disregarded there appears to have been no relationship between the amounts of calcium in the soil solutions and those in the juice of the plants.

In plants grown on four of the soil types the concentration of calcium was less in the juice of mature stems than in that of young stems, whereas in the plants from the other two types it was slightly higher. During the intermediate growth period the concentration of calcium varied greatly, but appeared to reach its highest point when the plants were 6 to 8 weeks old.

### *Juice of leaves*

Although marked differences were found in the amounts of calcium present in the juice of pea leaves obtained from plants grown on the different soil

TABLE 6  
*Calcium content of the expressed juice of pea stems at different stages of growth on different soil types*

SOIL TYPE	STAGE OF GROWTH				
	3 weeks	6 weeks	8 weeks	Budding	Maturity
	per cent	per cent	per cent	per cent	per cent
<i>Alkaline soils</i>					
Onaway.....	0.164	.....	0.114	0.109	0.142
Brookston.....	0.125	0.143	0.114	.....	0.093
Plainfield.....	0.125	0.132	0.136	0.071	0.104
<i>Acid soils</i>					
Kewanee.....	0.128	0.173	0.105	.....	0.220
Miami.....	0.121	0.185	0.145	.....	0.142
Hillsdale.....	0.103	0.177	0.065	0.086	0.095

types, as appears in table 7, there was so much fluctuation during the growth period that it appears to be impossible to associate the amounts present with any of the soil properties which were considered. Likewise it is only possible to say that in the plants obtained from all of the soil types the concentration of calcium was greater in the juice expressed from the mature leaves than in that expressed from the young leaves and that it varied greatly because of soil type during the intermediate period of growth.

The concentration of calcium was greater in the expressed juice of the leaves at all times than in that of the stems and the difference became greater as the growth period advanced.

## MAGNESIUM CONTENT OF GREEN PEA STEMS AND LEAVES AT DIFFERENT STAGES OF GROWTH ON DIFFERENT SOIL TYPES

The magnesium content of plants studied previously (2, 3) was found to fluctuate so much that any study of its relationship to modifying factors was difficult. A cursory examination of the data presented in the following pages indicates that such difficulty is to be encountered here.

*Stems*

In table 8 are given the data representing the magnesium contents of the stems of green pea plants at different stages of growth on the several soil types.

TABLE 7  
*Calcium content of the expressed juice of pea leaves at different stages of growth on different soil types*

SOIL TYPE	STAGE OF GROWTH				
	3 weeks	6 weeks	8 weeks	Budding	Maturity
	<i>per cent</i>	<i>per cent</i>	<i>per cent</i>	<i>per cent</i>	<i>per cent</i>
<i>Alkaline soils</i>					
Onaway.....	0.206	.....	.....	0.372	0.126
Brookston.....	0.145	0.260	0.235	.....	0.358
Plainfield.....	0.206	0.236	0.170	0.260	0.272
<i>Acid soils</i>					
Kewanee.....	0.162	0.298	0.184	.....	0.382
Miami.....	0.147	0.315	0.185	.....	0.558
Hillsdale.....	0.098	0.296	0.223	0.205	0.199

Great differences existed in the amounts of magnesium present in the plant material obtained from the different soils and the greatest range of variation appeared during the intermediate stages of growth, the contents at the beginning and close of the growth period being more uniform.

Generally a larger percentage of magnesium was present in the stems obtained from the heavy soils during the early part of the growth period. There appears to have been a tendency for the amount of magnesium to increase in the stems of plants grown on the sandy soils as the growth period advanced, whereas a decrease occurred in the stems of plants obtained from the heavy soils. This resulted in about a uniform content at maturity as far as the effect of soil texture was concerned.

There is no evidence that the magnesium content of the pea stems was influenced by either the reaction of the soil or the concentration of magnesium in the soil solution. Likewise the data given here and those in table 1 indicate that there was no relationship between the amounts of magnesium and the amounts of calcium present in the pea stems.

*Leaves*

Apparently the magnesium content of the leaves of pea plants grown on the different soil types was more uniform than that of the stems of the same plants. This is brought out by the data in table 9, where differences of less magnitude are evident throughout the period of growth.

The amounts of magnesium present in the green pea leaves varied independently of any of the soil characteristics studied here, insofar as could be determined by the data of table 9.

TABLE 8

*Magnesium content of green pea stems at different stages of growth on different soil types*

SOIL TYPE	STAGE OF GROWTH				
	3 weeks	6 weeks	8 weeks	Budding	Maturity
	<i>per cent</i>	<i>per cent</i>	<i>per cent</i>	<i>per cent</i>	<i>per cent</i>
Plainfield.....	0.039	0.017	0.043	0.046	0.052
Hillsdale.....	0.052	0.013	0.017	0.046	0.039
Kewanee.....	0.032	0.066	0.026	.....	0.053
Onaway.....	0.062	.....	0.037	0.052	.....
Brookston.....	0.066	0.077	0.043	.....	0.052
Miami.....	0.066	0.046	0.026	.....	0.039

TABLE 9

*Magnesium content of green pea leaves at different stages of growth on different soil types*

SOIL TYPE	STAGE OF GROWTH				
	3 weeks	6 weeks	8 weeks	Budding	Maturity
	<i>per cent</i>	<i>per cent</i>	<i>per cent</i>	<i>per cent</i>	<i>per cent</i>
Plainfield.....	0.055	0.108	0.061	0.105	0.096
Hillsdale.....	0.063	0.099	0.052	0.079	0.083
Kewanee.....	.....	0.066	0.057	.....	0.070
Onaway.....	0.076	.....	0.053	0.108	0.109
Brookston.....	0.063	0.079	0.087	.....	0.118
Miami.....	0.071	0.082	0.052	.....	0.257

Greater amounts of magnesium were present in the green material of pea leaves than in that of pea stems at each stage of growth. Likewise there was an increased amount present in mature leaves as compared with that of young leaves on all of the soil types studied, resulting in a wider ratio in the two plant parts at maturity than in the early stages of growth.

## MAGNESIUM CONTENT OF THE EXPRESSED JUICE OF PEA STEMS AND LEAVES

*Stems*

Aside from the fact that the magnesium content of the juice of pea stems varied greatly in the plants grown on the different soil types, there is only one

significant feature brought out by the data of table 10. It is strikingly evident that the magnesium content of the juice of the stems obtained from plants grown on the two very acid soils was very low when the plants were 3 weeks old. However, on these soils a greater increase in concentration occurred in the magnesium content of the juice, resulting in a greater percentage of magnesium at maturity in the samples obtained from the very acid soils. Just what property of the soils or the plants induced this condition is not indicated.

TABLE 10  
*Magnesium content of the expressed juice of pea stems at different stages of growth on different soil types*

SOIL TYPE	STAGE OF GROWTH				
	3 weeks	6 weeks	8 weeks	Budding	Maturity
	per cent	per cent	per cent	per cent	per cent
Plainfield.....	0.058	0.037	0.037	0.028	0.043
Hillsdale.....	0.045	0.053	0.025	0.028	0.032
Kewanee.....	0.018	0.039	0.021	.....	0.064
Onaway.....	0.057	.....	0.027	0.036	0.048
Brookston.....	0.056	0.066	0.031	.....	0.041
Miami.....	0.011	0.067	0.043	.....	0.058

TABLE 11  
*Magnesium content of expressed juice of pea leaves at different stages of growth, on different soil types*

SOIL TYPE	STAGE OF GROWTH				
	3 weeks	6 weeks	8 weeks	Budding	Maturity
	per cent	per cent	per cent	per cent	per cent
Plainfield.....	0.049	0.071	0.056	0.053	0.059
Hillsdale.....	0.023	0.070	0.067	0.062	0.058
Kewanee.....	0.021	0.056	0.036	.....	0.059
Onaway.....	0.037	.....	0.062	0.088	0.039
Brookston.....	0.059	0.076	0.069	.....	0.092
Miami.....	0.059	0.078	0.051	.....	0.171

Evidently there was no relationship between the texture of the soil or the amounts of magnesium present in the soil solutions and the concentration of magnesium in the juice of the stems.

#### *Leaves*

In table 11 are given the data showing the magnesium content of the expressed juice of the pea leaves. Marked differences existed in the magnesium contents of the juice of the leaves obtained from the different soil types and it appears that these contents were greater in the plants grown upon the heavy soil types during the entire growth period than they were in the plants obtained

from the light soils. However, there was no correlation between the magnesium present in the plant juice and that present in the soil solution, nor was there evident any influence of the reaction of the soil upon the amount of magnesium in the plant juice.

In the early stages of growth the concentration of magnesium was about equal in the juice of the stems and leaves but as the growth period advanced the concentration increased more rapidly in the juice of the leaves with the result that in the mature stage it was higher here.

All of the data obtained in this work showed that there was always more calcium than magnesium present in the green plant material and in the juice of the pea plant.

TABLE 12  
*Green weight of peas at different stages of growth on different soil types*  
Weight in grams of 7 plants

SOIL TYPE	STAGE OF GROWTH		
	3 weeks	6 weeks	8 weeks
	gm.	gm.	gm.
Plainfield.....	9.10	21.7	65.5
Kewanee.....	7.28	16.9	61.2
Onaway.....	7.25	....	54.6
Hillsdale.....	11.90	29.0	82.7
Brookston.....	8.26	21.0	46.5
Miami.....	7.14	9.1	27.7

GREEN WEIGHT OF PEAS ON DIFFERENT STAGES OF GROWTH ON DIFFERENT  
SOIL TYPES

The green weights of pea plants produced on the different soil types were obtained for only three stages of growth, because of the extent to which the leaves dropped as the plants approached maturity. These data appear in table 12.

When the plants were 3 weeks old, their green weight was nearly equal on all of the soil types, but as the growth period advanced, the rate of growth changed markedly. Plants grown on Hillsdale and Plainfield soils made the most rapid growth and those grown on Miami and Brookston soils made the least rapid growth. The data showing the calcium and magnesium contents of the plants indicate that the rapidly growing plants were usually low in these two elements, whereas the slowly growing plants were usually high in them. It thus appears that at least some of the differences noted in the calcium and magnesium contents of the plants may be attributed to differences in the rate at which the plants were making growth as well as to the differences in the characteristics of the soils.

PROPORTION OF LEAVES AND STEMS OF PEAS GROWN IN THE GREENHOUSE ON  
DIFFERENT SOIL TYPES

In table 13 are given the green weights of the stems and leaves of peas at several growth stages. At 3 weeks of age there was little variation in the proportion of leaves and stems on the different soil types, but as the plants became older, greater differences appeared.

There was an increase in the proportion of stems to leaves during the period of growth until it became about constant at the budding stages. In the beginning the average percentages were 40 for stems and 60 for leaves. When the plants were 8 weeks old, the average percentage of stems had become 58.2 and that of leaves 41.8; which about reversed the situation found at the age of 3 weeks. At the 3-week stage of growth the proportion of stems and leaves in peas was about the same as was found for beans, but in beans the proportion of stems decreased, while in peas it increased with the age of the plant.

TABLE 13  
*Proportion of leaves and stems of peas at different stages of growth on different soil types*

SOIL TYPE	STAGE OF GROWTH							
	3 weeks		6 weeks		8 weeks		Budding	
	Stems	Leaves	Stems	Leaves	Stems	Leaves	Stems	Leaves
	per cent	per cent	per cent	per cent	per cent	per cent	per cent	per cent
Plainfield.....	36.1	63.9	40.5	59.5	64.1	35.9	55.6	44.4
Kewanee.....	40.9	59.1	45.5	54.5	60.4	39.6	....	....
Onaway.....	39.1	60.9	....	....	56.4	43.6	57.2	42.8
Hillsdale.....	42.6	57.4	45.0	55.0	55.6	44.4	53.8	46.2
Brookston.....	40.0	60.0	33.3	66.7	56.5	43.5	....	....
Miami.....	40.4	59.6	41.7	58.3	56.5	43.5	....	....

SUMMARY AND CONCLUSIONS

In this work the influence of the growth of field peas upon the calcium and magnesium content of the soil solution and upon the reaction of the soil was observed. Likewise, variations in the calcium and magnesium content of pea stems and leaves and in their juice when obtained from plants grown on different soil types were studied. The relationship of certain characteristics of the different soil types to the amounts of calcium and magnesium present in the pea plants was considered.

Growing pea plants greatly reduced the amounts of calcium and magnesium present in the different soil solutions. They also tended to decrease the acidity of strongly acid soils and to increase that of alkaline or nearly neutral soils.

The calcium and magnesium content varied greatly in the pea plants grown on the different soil types. On soils of similar texture and reaction, the amount of calcium present in the pea plant varied directly with the amount



present in the soil solution. Soil texture and soil reaction influenced the calcium content of the peas to the extent of obscuring the effect of the concentration of the soil solution if not allowed for. The magnesium content of the plants was very irregular and appeared to be influenced more by soil texture than any other characteristic of the soils studied here.

There was more calcium and magnesium present in the tissue and in the juice of pea leaves than in the tissue and the juice of the stems. As the plants became older, the concentration of calcium and magnesium increased in the tissue and juice of pea leaves, whereas it sometimes increased and sometimes decreased in the tissue and juice of stems.

Greater amounts of calcium than of magnesium were always present in the tissue and in the juice of pea stems and leaves.

It appeared that the calcium and magnesium content was higher in slowly growing plants than in those making a rapid growth.

The proportion of stems was smaller than that of leaves in the young plants but became greater as the plants advanced in growth.

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## THE ULTIMATE NATURAL STRUCTURE OF SOILS

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The texture of soils is usually defined as the ultimate size of soil particles, and structure of soils is commonly defined as the arrangement of these soil particles under actual soil conditions. This arrangement or structure assumes all sorts of forms under actual soil conditions, depending largely upon the soil type and treatment. It may be in the form of single grained particles, compound particles or granules, large and small blocks or clods.

The structure of soils as found under field conditions is not the ultimate and natural structure. This kind of structure is dependent on, and is the result of, many external factors, such as degree of moisture at which soil is worked, whether the soil has been puddled or not, and amount of work or degree of pressure applied in obtaining a proper tilth. In other words, this structure is only a temporary, accidental, artificial, and changeable condition.

Soils, however, appear to have a natural, ultimate, and stable structural condition. That is to say, the molecular, cohesive, adhesive, and cementing forces and the type tend to produce or give a soil a structure that is naturally and ultimately stable or more or less permanent and requires external energy or force to destroy it. For instance, in dispersing soils for mechanical analysis, it is this stable, ultimate, natural structure that is being destroyed, and as is well known, in some soils it is very hard to destroy it even with the application of an enormous amount of external energy.

This natural, ultimate, and stable structural condition of soils seems never to have been measured or studied; and the main reason for it is undoubtedly the lack of methods.

In 1924 (1) and also in 1927 (2) work was presented showing that when soils in the dry condition are placed in an excess of water they tend to disintegrate or slake into single or compound particles of various sizes. It was also revealed that on account of this principle, water plays a tremendously important rôle in producing and keeping a good tilth in soils.

An experimental test of the hydrometer method, developed for studying the texture of soils (3), for the study of the ultimate natural structure of soils seems to have proved successful.

It was found that when soils in dry condition were placed in an excess of water they would immediately begin to disintegrate or slake into particles or granules of various sizes. These particles or granules seemed to be in an ultimate natural size and stable condition, because according to the hydrometer method they would not get smaller upon standing in water for an indefinite length of time, nor upon gentle shaking. Indeed, allowing the soils to stay in

water for five days, or shaking them by hand in a liter cylinder from 6 to 30 times produced results that remained quite constant or changed very little. It would take very long and vigorous shaking, or the application of a considerable amount of energy, to break up these particles or granules from their natural, stable condition.

It seems quite certain, therefore, that soils have a natural, ultimate stable structure which is definite for any one soil, and that the phenomenon of slaking presents a natural and logical means of measuring accurately this structure. Indeed, it now appears that slaking is a fundamental phenomenon and the results it yields in soils with water are definite in character. That is to say, soils disintegrate or undergo a mechanical dissolution, somewhat similar to a chemical dissolution, into their natural, ultimate structure, which is stable and can only be destroyed by the application of external energy. This mechanical dissolution of soils is brought about by the attraction of the soil particles for water, and the film of water intervening or surrounding the particles destroys their force of cohesion or attraction for each other.

It is the object of this paper, therefore, to present data on the measurement of the natural ultimate structure of the various types of soils, by means of the phenomenon of slaking and the hydrometer method. In other words, it is the measurement of the texture of the natural ultimate structure of soils.

#### METHOD AND PROCEDURE

In order to facilitate the rate, insure completeness of slaking, and eliminate any mechanical handling which would tend to cause artificial dispersion, a suitable method had to be devised. The method that was worked out and finally adopted consisted of placing the soil into a bag made of 2-mm. window screen and suspended in the special 1000-cc. hydrometer cylinders filled with water to the proper mark (3). As soon as the soil was dropped into the wire bag and came in contact with the water it would immediately begin to slake into particles or granules of various sizes, and these particles would go through the 2-mm. wire screen and fall into the mass of water or to the bottom of the cylinder. To prevent the particles or granules from accumulating in the bag as they slaked from the mass of soil, the bag was pushed gently up and down in the water occasionally and the slaked portion of the soil would immediately fall into the water. As the slaked portion of the soil would leave the bag, more surface of the unslaked soil would be exposed, which in turn would slake at a greater rate. The bag would be left in the water with occasional gentle pushing up and down, until all the soil had slaked and fallen out of the bag. To assure complete slaking, however, the soils would be left in the water at least two hours.

The use of the wire bag was helpful because (a) it prevented the shielding effect of the slaked portion of the soil in the unslaked portion, (b) the rate of slaking was thereby considerably hastened, and (c) it showed definitely when the soil was completely slaked.

Since it was the object of this investigation to study the natural ultimate

structure of soils, only soils in the natural field conditions were used. That is to say, great care was taken not to pulverize the soil in any way but to use it just as it would exist in the ground.

On the other hand, it was found that the phenomenon of slaking requires that the soil be dry. In other words, unless a soil is in a dry state it will not break down in water into its ultimate natural structure. This may be attributed to the fact that the phenomenon of slaking is brought about by the attraction of the soil particles for water, and the attractive forces for water are greatest only when the soil is dry. Hence, all the soils that were used in this investigation were in an air-dry condition.

The amount of air-dry soil employed was equivalent to 50 gm. on an oven-dry basis, in every case. This weighed amount of soil, would be dropped, as previously stated, into the wire bag suspended in water in the cylinder and allowed to slake. Any gravel that remained behind would be weighed and taken into consideration in the final calculation of the results.

After a soil had completely slaked, 5 cc. *N* KOH was added and then it was shaken six times by placing one palm on the mouth of the cylinder and turning the latter completely upside down and back three times. Then the cylinder was placed on a table, the time being noted immediately, the hydrometer put in the cylinder, and readings taken at the end of 10, 30, and 60 seconds and also at the end of 15 minutes.

It may seem that it is almost impossible to take hydrometer readings at the end of 10 seconds. It is true that it is a somewhat difficult test, but after a little experience it can be done rather easily. There is no difficulty, however, in taking readings at the end of 30 seconds.

The hydrometer readings are then translated directly into size of particles. This is accomplished by the aid of Stoke's law as shown in a previous communication (3). According to Stoke's law, and basing the calculations on a column of liquid  $32\frac{1}{2}$  cm. high and a temperature  $20^{\circ}\text{C}.$ , the sizes of particles that will fall or still stay in suspension at the various times are as follows:

<i>Time of sedimentation</i>	<i>Diameter of particles</i> <i>mm.</i>	<i>Time of sedimentation</i>	<i>Diameter of particles</i> <i>mm.</i>
10 seconds	0.1914	11 hours	0.00303
30 seconds	0.11009	12 hours	0.0029
60 seconds	0.07785	13 hours	0.00279
2 minutes	0.055050	14 hours	0.00270
5 minutes	0.034814	15 hours	0.00259
15 minutes	0.02010	16 hours	0.0025
30 minutes	0.014212	17 hours	0.00243
60 minutes	0.01005	18 hours	0.002369
2 hours	0.0071	19 hours	0.002307
3 hours	0.0056	20 hours	0.00223
4 hours	0.00502	21 hours	0.00219
5 hours	0.0045	22 hours	0.00214
6 hours	0.0041	23 hours	0.00209
7 hours	0.0038	24 hours	0.00205
8 hours	0.00355	48 hours	0.00145
9 hours	0.00335	96 hours	0.001025
10 hours	0.00318		

The foregoing figures for size of particles signify the upper limit of size of any particle that will stay in suspension at any given time. For instance, at the end of one minute the upper limit of any particle that may still stay in suspension is 0.077846 mm. in diameter, at the end of one hour 0.01005 mm., etc.

In the present investigation, however, the hydrometer readings were taken at only four different periods, after 10, 30, and 60 seconds, and after 15 minutes. Consequently the largest particles, or upper size limit of particles that would still be in suspension would be 0.1914, 0.11009, 0.07785, and 0.02010 mm., respectively.

It is at once seen that the largest size of particles that can be measured by the hydrometer and Stoke's law is about 0.2 mm., which is the border-line between medium and fine sand. It is unfortunate that particles larger than the above cannot be measured by this combined method. But even with this limitation the method yields much information concerning the ultimate natural structure of soils, which is of great significance, as will be seen.

In order to get a comparison between the ultimate natural structure and the ultimate texture of soils, the same sample of soil that was used to measure the structure was dispersed by the special soil dispersing machine, previously described (3) and hydrometer readings were taken at the same periods. It was believed that such a comparison would possess distinct value. For instance, if a soil when dispersed shows that it contains 85 per cent of clay and before dispersing shows that it contains only 3 per cent of clay, then it must be assumed that nearly all the clay portion of this soil exists, or slakes naturally, in particles or granules much larger than the clay size. If, on the other hand, a soil when dispersed shows that it contains 25 per cent clay and before dispersion 11 per cent clay, then it follows that a large portion of the clay of this soil exists, or slakes naturally, in particles of the clay size and a comparatively smaller portion in larger particles or granules.

It might be thought that the addition of potassium hydroxide would affect the results. As stated in previous paper (3), however, the main function of the presence of the potassium hydroxide seems to be to stabilize the soil suspension rather than to increase dispersion.

#### EXPERIMENTAL RESULTS

Before the actual experimental data are presented on the ultimate natural structure of soils, it is necessary to present first results showing that when a soil slakes in water it slakes into particles, or granules, which are rather surprisingly stable and do not easily become smaller when gently shaken or when allowed to remain in water for an indefinite length of time. It is really this rather striking stability that makes it possible to measure the natural ultimate structure of soils.

The results given in table 1 are typical of a large number of soils examined repeatedly. As previously stated, these results were obtained by allowing the soil to slake completely in the cylinder, and then placing one palm on the

mouth of the cylinder, and turning the latter completely upside down and back three times and then taking the hydrometer readings. This form of shaking would be repeated many times.

TABLE 1  
*Stability or the resistance of the naturally slaked particles or granules of soil to become smaller when shaken gently or allowed to stand in water*

(Results show percentage of soil material still in suspension whose upper limit is indicated at each period)

	TIME AND DIAMETER			
	10 seconds, 0.1914 mm.	30 seconds, 0.1101 mm.	60 seconds, 0.0778 mm.	15 minutes, 0.0201 mm.
	per cent	per cent	per cent	per cent
<i>Michigan clay</i>				
Shaken 6 times.....	25.0	12.0	8.0	3.0
Shaken 12 times.....	25.0	12.5	9.0	3.1
Shaken 18 times.....	26.0	13.8	9.4	3.4
Shaken 24 times.....	26.0	14.0	10.0	3.4
Shaken 30 times.....	26.0	14.0	11.0	3.5
Completely dispersed.....	88.5	86.3	84.8	83.6
<i>Missouri silty clay</i>				
Shaken 6 times.....	41.0	25.0	19.0	4.0
Shaken 12 times.....	41.0	27.0	20.0	4.0
Shaken 18 times.....	41.0	28.0	22.0	4.5
Shaken 24 times.....	41.0	28.5	23.0	5.2
Shaken 30 times.....	42.0	29.0	24.0	6.0
Completely dispersed.....	87.5	82.4	80.0	59.7
<i>Michigan clay</i>				
Stood 1 hour, shaken 6 times.....	26.8	14.3	11.6	3.8
Stood 24 hours, shaken 12 times.....	26.8	14.7	12.1	4.1
Stood 48 hours, shaken 18 times.....	27.3	14.2	12.7	3.9
Completely dispersed.....	88.5	86.3	84.8	83.6
<i>Missouri silty clay</i>				
Stood 1 hour, shaken 6 times.....	41.8	26.1	18.8	4.2
Stood 24 hours, shaken 12 times.....	42.5	27.3	21.1	4.2
Stood 48 hours, shaken 18 times.....	43.1	28.2	22.6	4.9
Completely dispersed.....	87.5	82.2	80.0	59.7

It is at once apparent, therefore, that when soils slake in an excess of water into particles and granules, these particles and granules are stable and in equilibrium, and neither gentle shaking nor long standing in water will decrease their size. Hence, they must represent the ultimate, natural structure

of soils. Some soils that slake with great difficulty may show greater increase of dispersion with greater number of times of shaking than is shown in the above soils.

The term "gentle shaking" is used. This term, however, is only relative. The shaking is gentle in comparison to the dispersing machine, wherein the soil particles are whirled around at a speed of over 10,000 revolutions per minute, but it is quite vigorous when it is considered that a soil is shaken 6 to

TABLE 2  
Percentage of soil material still in suspension whose upper limit of size is indicated at each period  
(Results are intended to indicate the mechanical analysis of the ultimate natural structure of soils as compared to their ultimate texture or mechanical analysis)

	NATURALLY SLAKED				MECHANICALLY DISPERSED			
	Time and diameter							
	10 seconds, 1.1914 mm.	30 seconds, 0.1101 mm.	60 seconds, 0.0778 mm.	15 minutes, 0.0201 mm.	10 seconds, 0.1914 mm.	30 seconds, 0.1101 mm.	60 seconds, 0.0778 mm.	15 minutes, 0.0201 mm.
	per cent	per cent	per cent	per cent	per cent	per cent	per cent	per cent
1. Fresno fine sandy loam.....	48.0	33.0	25.0	5.6	46.0	38.0	30.0	11.10
2. Susquehanna fine sandy loam.....	35.0	18.5	14.5	5.0	40.0	26.0	18.0	10.00
3. Portsmouth sandy loam.....	28.0	17.0	12.0	3.0	40.0	28.0	22.0	8.4
4. Hagerstown loam.....	17.0	10.0	7.5	2.3	75.0	70.0	67.5	48.5
5. Michigan silt loam.....	51.0	38.0	34.0	14.0	58.0	54.0	50.0	17.4
6. Grundy silt loam.....	68.0	50.0	38.5	5.0	88.9	85.0	76.0	34.0
7. Antrim county silt clay.....	38.5	27.0	23.5	8.0	74.8	72.0	68.0	45.0
8. Brookston silt loam (surface).....	32.0	19.0	14.0	5.0	51.0	43.0	39.0	25.5
9. Miami silt loam (0-6 inches).....	38.0	24.0	21.0	7.0	56.0	45.0	41.0	22.0
10. Napanee silt loam (0-6 inches).....	38.0	26.0	22.0	11.0	58.2	54.0	53.0	38.0
11. Ontonagon silt loam (0-6 inches)....	56.0	41.0	30.0	9.0	86.0	82.0	75.0	54.0
12. Minn Clyde silt loam.....	46.0	28.0	13.0	8.0	79.6	76.0	72.0	35.0
13. Miami silt loam C (40-60 inches)....	50.0	30.0	13.0	9.0	80.3	76.0	72.0	52.0
14. Miami silt loam B (8-30 inches).....	17.0	13.0	11.0	4.5	65.3	62.0	59.0	40.0
15. Susquehanna clay C.....	28.0	14.0	9.0	4.5	71.0	66.0	63.0	58.0
16. Residual limestone clay.....	26.0	13.0	8.5	3.3	88.0	86.0	85.0	83.0
17. Alkali soil.....	52.0	34.0	24.0	7.5	56.0	37.0	28.0	18.5
18. Putman silty clay B.....	42.3	26.2	18.8	5.3	88.6	83.1	80.6	60.1

30 times by allowing it to fall each time a distance of over 16½ inches in the cylinder.

The final results are shown in table 2.

A critical examination of the results in table 2 reveals many interesting and significant facts regarding the ultimate natural structure of soils, as well as their ultimate texture. A comparison of the two columns under the 15-minute period readily demonstrates that when soils slake, they have comparatively



little material under 0.0201 mm. This is true not only with the sandy loams and loams but even with the heaviest clays. For instance soil no. 16 when dispersed contains 83.0 per cent material under 0.0201 mm. whereas before it is dispersed, or when it naturally slakes, it has only 3.3 per cent under the same size of particles. The amount of soil material under 0.0201 mm. is less than 10 per cent in nearly all the soils when they are allowed to slake, but when they are dispersed the amount of material under this size increases from about  $1\frac{1}{2}$  times to more than 25 times. Hence the texture of the ultimate natural structure of soils is mainly coarse.

In this connection it is very interesting and important to note that sandy loams and loams which have a relatively small amount of total clay have relatively and in many cases, absolutely, more fine slaked material than the clays and clay loams which possess a very high clay or colloidal content. For instance soil 2 contains only 10 per cent total material under 0.0201 mm., whereas in the slaked condition it contains 5 per cent. On the other hand soils 11, 13, 15, and 16 contain 54, 52, 58, and 83 per cent total material respectively under 0.0201 mm., but in the slaked condition they contain only 9, 9, 4.5, and 3.3 per cent, respectively, of the same fine material.

This same kind of difference seems to exist also between surface and sub-surface soils. As a rule, surface soils seem to have somewhat more fine material in the slaked condition than the subsoils, even though the latter may contain considerably more total clay or colloids. For instance, surface soils 9 and 10 contain 7 and 11 per cent material under 0.0201 mm. and they contain 22 and 38 per cent, respectively, of total material of the same size while many of the subsoils which contain 60 and 80 per cent of the fine material do not contain any more of the same fine material in the slaked condition. Indeed, many of the substrate soils as Miami Silt loam B tend to slake into large pieces.

A comparison next of the results in the two columns under the 10-second period, also show some very interesting and significant contrasts in the various types of soil. One of the most significant things brought out is the fact that clay soils, and especially those of the deeper horizons, have more particles or granules larger than 0.1914 mm. than do the light types of soils, which contain only a moderate or very little total clay content. For instance, soil 1 which contains only 11 per cent material under 0.0201 mm. contains 48 per cent under 0.1914 mm. or 52 per cent above this size; whereas soil 4 which contains 48.5 per cent material under 0.0201 mm. has only 17 per cent under 0.1914 mm., or 83 per cent above this size. Similar differences are seen in most of the other soils. Apparently, therefore, the more clay a soil contains, and the purer this clay is, the greater, as a rule, is its tendency to slake or disintegrate into larger particles or granules, or pieces. This may be attributed to the greater cohesive force, for like has greater attraction for like.

A comparison of the results in the respective columns under the 30- and 60-second period shows the same tendencies for the various soils, with slight

decrease of variations, as those revealed in the columns under the 10-second and 15-minute periods, which are the extremes.

At this point it would be proper to ask whether the ultimate natural structure of soils when destroyed by dispersion or puddling, remains permanently in that destroyed condition or whether it is in time restored. That is to say, if a soil is dispersed by the machine, so that its particles are reduced to their ultimate size, will it regain its former or original structure after it is dried again, or will it remain indefinitely in the dispersed condition.

The answer to this question is given by the results in table 3. These results were obtained by allowing the soils to slake naturally. Their mechanical analysis was then ascertained by the hydrometer method already described. These naturally slaked soils were then dispersed by the special dispersing machine and their mechanical analysis was again measured. The dispersed soils were then poured into large beakers and evaporated to dryness. The dried soils were wetted and dried at least once or twice. These dispersed soils in the dry condition were then dropped into the wire bag suspended in water in the cylinder and allowed to slake naturally. After the soils had completely slaked they were shaken 6 to 10 times and their mechanical analysis was determined.

Examining first the results in the three columns under the 15-minute period (table 3) we see at once that the dispersed soils tend to go back to their original natural structure by the process of drying and wetting. This is revealed by the fact that the amount of the fine material under 0.0201 mm. is smaller in the slaked dispersed soils than in the mechanically dispersed soils, and tends to approach that in the naturally slaked soils. For instance, soil 1 has 83 per cent of fine material under 0.0201 mm. when mechanically dispersed, but it has only 5.5 per cent of the same size when this dispersed soil is dried, wetted, and slaked. While in the naturally slaked condition, this soil has 3.3 per cent of the same fine material. Soil 6 has 35 per cent of its material under 0.0201 mm. when mechanically dispersed, 13.5 per cent when the mechanically dispersed soil is slaked, and 8 per cent when the natural soil is slaked.

Apparently, therefore, when the natural structure of a soil is destroyed and reduced to the ultimate size particles, this condition is not stable or in equilibrium and upon drying, these ultimate size particles tend to unite and go back to the natural, ultimate structure, which is stable and in equilibrium. The ability of the ultimate size particles to go back to the natural structural condition, varies with the soil. With some soils, they go back at once, as in soil 1; with other soils they go back more slowly, and they require a larger number of times of wetting and drying to do it.

Examining next the results in the various columns under the 10-, 30-, and 60-second periods, we note that the amount of material under 0.1914, 0.1101, and 0.0778 mm., is considerably greater in the slaked, dispersed soils than in the natural, slaked soils. Apparently, particles of this size in the dispersed soils do not tend to go back to their original structure as easily as those below



0.0201 mm. It must be remembered, however, that the larger sizes represent separated sands, which would not be expected to form larger particles or granules unless they were cemented or united by the finer particles. Hence, these results are just what should be expected. Under further wetting and drying and thoroughly mixing, they too would ultimately go back to the original structure or to that shown when natural soils are slaked.

Soil 10 in table 3 merits special attention. It is composed entirely of pure

TABLE 3

*Effect of drying and wetting on the structure and texture of soils which had been mechanically dispersed*

(Results indicate percentage of soil material still in suspension whose upper limit of size is indicated by each period)

	NATURAL SOIL SLAKED				NATURAL SOIL MECHANICALLY DISPERSED				DISPERSED SOIL EVAPORATED TO DRYNESS, WETTED AND DRIED, AND ALLOWED TO SLAKE			
	Time and diameter											
	10 seconds, 0.1914 mm.	30 seconds, 0.1101 mm.	60 seconds, 0.0778 mm.	15 minutes, 0.0201 mm.	10 seconds, 0.1914 mm.	30 seconds, 0.1101 mm.	60 seconds, 0.0778 mm.	15 minutes, 0.0201 mm.	10 seconds, 0.1914 mm.	30 seconds, 0.1101 mm.	60 seconds, 0.0778 mm.	15 minutes, 0.0201 mm.
	per cent	per cent	per cent	per cent	per cent	per cent	per cent	per cent	per cent	per cent	per cent	per cent
1. Residual limestone clay.....	26.0	13.0	8.5	3.3	88.0	86.0	85.0	83.0	65.0	42.0	32.0	5.5
2. Susquehanna clay C.....	28.0	14.0	9.0	4.5	71.0	66.0	63.0	58.0	65.5	52.0	45.0	22.0
3. Naponee silt loam (0-6 inches).....	38.0	26.0	22.0	11.0	58.2	54.0	53.0	38.0	38.0	26.0	21.0	14.0
4. Ontonagon silt loam (0-6 inches).....	56.0	41.0	30.0	9.0	86.0	82.0	75.0	54.0	65.8	56.5	47.5	21.5
5. Hagerstown loam....	17.0	10.0	7.5	2.3	75.0	70.0	67.5	48.5	66.0	51.0	44.5	17.5
6. Minn clyde silt loam..	46.0	28.0	13.0	8.0	79.6	76.0	72.0	35.0	71.0	61.8	49.5	13.5
7. Miami silt loam B....	17.0	13.0	11.0	4.5	65.3	62.0	59.0	4.0	64.5	63.5	44.5	22.5
8. Brookston silt loam (0-6 inches).....	32.0	19.0	14.0	5.0	51.0	43.0	39.0	25.5	36.8	27.0	24.0	8.0
9. Michigan silt loam....	51.0	38.0	34.0	14.0	58.0	54.0	50.0	17.4	55.0	43.0	38.5	8.9
10. Pure colloids from soil 2.....	.....	.....	.....	.....	100.0	100.0	100.0	100.0	7.0	5.0	4.5	3.5

colloids which were extracted by the process of decantation from soil 15 in table 2. These pure colloids were evaporated to dryness and then allowed to slake, as in the case of the other soils. These colloids when in dispersed condition gave 100 per cent colloids in suspension by the hydrometer method. Now, when these colloids were evaporated to dryness and then allowed to slake, they did not slake into fine particles again but rather into medium and large flat pieces, which would not pass the 2-mm. wire bag; and, as shown in the table, hardly any material stayed in suspension.

The refusal of these pure soil colloids to slake again into fine particles is a representative phenomenon in soils. It goes to support the statement already made, that the higher and purer is the clay content in soil, the coarser is the structure into which it slakes. This might be attributed to the fact that the cohesive, adhesive, and attractive forces are greater in such materials and these forces prevent them from slaking into very fine particles.

The tendency of the pure colloids as well as the highest clay content soils and subsoils to slake into coarser material than do the lighter textured soils, is in conformity with the behavior of these soils under field conditions. For instance, it is common knowledge that it is almost impossible to work certain clay soils and subsoils of very high clay content into a fine tilth. On account of the great adhesive, cohesive, attractive, and cementing forces, these soils have a predominant tendency to break into clods. On the other hand, light textured soils have a predominant tendency to break into rather fine textural tilth. Hence, the experimental results here obtained have a close relation to practical experiences, and careful judgment has to be employed in interpreting them.

Since the structure into which soils naturally slake is the ultimate, natural, and stable structure, then it would seem that under field conditions the natural tendency of soils would be to maintain this structure. Of its own accord, this structure would not get finer or coarser unless it was brought about by some external agent, such as the use of implements in the preparation of the seedbed. But even then, this change of the natural, ultimate structure would be temporary, for the process of wetting and drying would tend to bring it back to its original natural and stable condition.

Under field conditions the natural, ultimate structure of soils may or may not be seen. What is usually seen is the accidental, artificial, and changeable structure.

Finally, it must be emphasized (a) that on account of the tendency of soils to slake into their natural, ultimate structure, (b) because this natural, ultimate structure tends to be stable, and (c) since the soil particles have such a strong tendency to go back to the natural, ultimate structure when it is once destroyed, the work previously reported (1), that water is the greatest single agent in producing and maintaining soil granulation, is well confirmed and supported by the present findings.

#### SUMMARY

When soils in the natural state but dry condition are placed in an excess of water they slake or disintegrate into particles and granules of various sizes.

Slaking these particles and granules in a large quantity of water, gently but quite vigorously, does not decrease their original size or slaked condition. To make them smaller or break them up further, a large amount of external energy or force has to be applied.

The size into which the particles and granules slake naturally, seems to be remarkably stable and in equilibrium, and a large amount of force has to be applied to make this original size smaller.

Since the size of the particles and granules into which soils slake in water has such marked stability, it is believed that these particles and granules constitute the natural, ultimate structure of soils. In other words, when natural, dry soils are placed in excess of water, they slake into their ultimate, natural structure.

The ordinary structure that is seen under field conditions is not the natural, ultimate structure. This field structure is the accidental, artificial, changeable, and temporary structure.

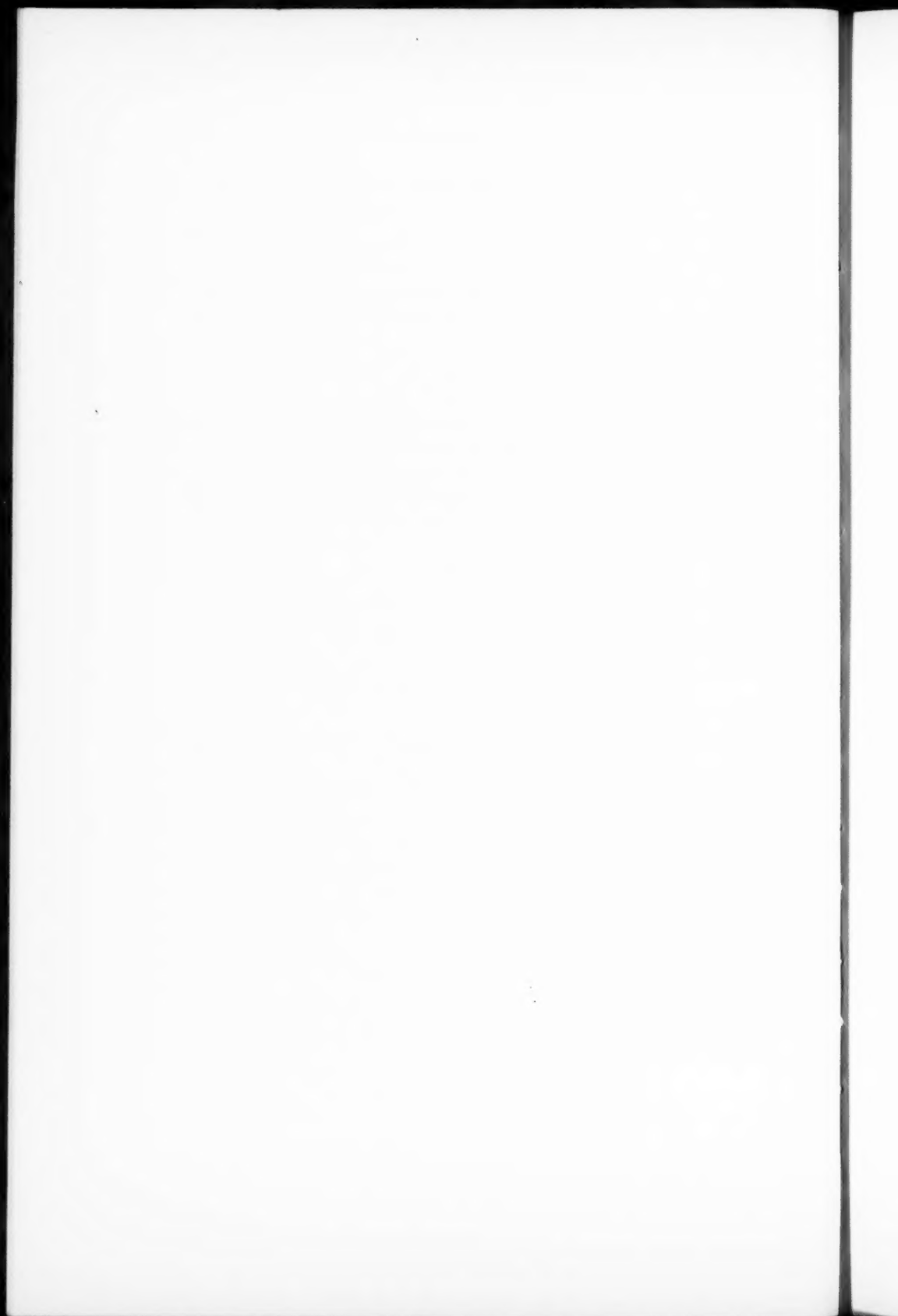
By means of the hydrometer method it is possible to make a mechanical analysis of this natural, ultimate structure and thereby ascertain the size and proportion of the various particles and granules. In other words, it seems that it is as possible now to determine the texture of the natural, ultimate structure of soils as it is to determine the ultimate size of particles.

The experimental data presented would seem to support those views.

It would appear that this natural ultimate structure of soils ought to form the basis for the study of many soil physical properties such as percolation, penetration, etc.

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## SOIL PROFILE STUDIES: I. SOIL AS AN INDEPENDENT BODY AND SOIL MORPHOLOGY<sup>1</sup>

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The study of soils began not as an independent branch of science, but as an adjunct to some established scientific discipline, such as geography, geology, mineralogy, chemistry, or a combination of some of these. The scientific study of soils began in the laboratory, not in the field. As a result, soil morphology made no progress until extensive studies in the field forced the workers to describe the soil, give its morphological characters, such as color, structure, constitution, consistency, and texture. But in the early period of field study, it was not morphology of soils, but of soil material. Not until the soil was recognized as an independent natural body did scientific soil morphology find its place in the scheme of soil studies and became the valuable aid in unravelling the problems connected with soils.

### HISTORICAL

#### *Soil science as an independent science*

Because of its geographic position Russia presented an ideal geographic unit for the systematic study of soils. The vast stretches of the plain in European Russia with its fairly homogeneous character of topography at its gradual change of climatic conditions, expressed by the temperature and moisture relationships, as one moves from north to south made it imperative for the man in the field to study the soil in all its aspects. The consequence of this favorable physico-geographical position was that the Russian soil workers were the first to recognize the soil as a distinct and independent discipline of natural science. One may find hints to that effect in the work of other students of soils long before the savant and founder of the Russian soil science, Dokuchaev, announced his conclusions on the genesis of the Russian chernozem (black earth), which served as the basis for ushering in the new concept of soils as a historical, independent, natural body.

The natural scientists and early students of soils did not look upon soils as a distinct branch of natural science. Soils were appreciated simply as an object of agricultural activities for the human. The famous chemist, Berzelius,

<sup>1</sup> Journal Series paper of the New Jersey Agricultural Experiment Station, Department of Soil Chemistry and Bacteriology.

calls the soil "the chemical laboratory of nature in whose bosom various chemical decompositions and syntheses take place in large quantities in a hidden manner." [Quoted from Yarilov (77).] Sprengel (62) designates the soil as a changed mass of material derived from minerals containing the decomposition products of plants and animals.

Thaer (66) looked upon soils from a utilitarian standpoint. He divided soils into six species, each one being subdivided into several classes primarily on the basis of their utility. The species are: (a) Clay soils, (b) loam soils, (c) sandy loam and loamy sand, (d) sandy soils, (e) humus soils, and (f) limestone soils. This is a purely physical concept. Thaer calls the soil "a raw material from which the agriculturist obtains various organic products without which he could not persist."

The geologic point of view was developed by Berendt (5). He states: "Petrography and pedography, the study of native rocks, and soil science are branches of the same science—geognosy." He distinguishes between "Boden" and "Grund." The latter according to Berendt is "the native rock which appears to us in undisturbed solid form." The former is considered as "the part of native rock which comes out to the surface and which is mellowed mechanically because of its contact with the air, which changes it chemically."

The famous German soils man, Wahnschafte (71), does not agree with Berendt's definition of soils, which would exclude the marsh and peat soils. He therefore gives his own definition. "Soil is not a geognostic conception, but a cultural-technical, primarily an agricultural. . . . As soils I understand the upper mellow and earthy layer of the earth's mantle even though it may support but the poorest vegetation."

Fallou (16) occupies a unique place in the history of soil science. His work has not been appreciated and has been forgotten, although historically he may be looked upon as the founder of pedology. Fallou showed how the utility standpoint of the students of soils, up to his time, prevented the crystallization of a scientific appreciation of the nature of soils as such. He criticized severely the chemical theory of soils. He wrote: "Recently the millenium for agriculture was looked for from the chemist; it was thought that a chemical analysis of the soil would give a complete idea about the soil. . . . Soil science was recognized not as a science by itself, but as a branch of agricultural chemistry. . . . Soil science is an empirical science. Nature itself is its source. Observations on soils in their geognostic relations, or in their relation to the strata formation and to the underlying rock are of special importance." We may readily see that Fallou was a proponent of the purely geognostic or geologic point of view. He realized, however, that the science of geology does not exclude soil science as a distinct discipline. "Just as petrification is looked upon independently of the native rock which accompanies it and we have paleontology as a distinct science, in the same way, soils may be separated from the native rocks and investigated as a separate independent scientific discipline." The definition given by Fallou for soils is: "Soil is

decomposed, more or less disintegrated native rock distinct and separate from the compact, undisturbed native rock, with an admixture of organic materials; the rock has changed and metamorphosed in its form and infrequently also in its makeup. Soil as such does not therefore belong any more to the rock formation, but is a formation by itself."

Contemporaneously with Fallou, Dokuchaev began to develop his views on soils as a result of his extensive studies of the great belt of black earth found in Russia, known as chernozem.

Fallou, as has been pointed out, had recognized the soil as a distinct natural body, but he presented no evidence to that effect and for this reason his presentation of the soil classification did not stand the test and found no support in later years.

Richthofen (51), who followed in the footsteps of Fallou, did not differentiate sharply between soils and powdered and crushed rock materials obtained mechanically. Instead of connecting the regional distribution of soils with the physico-geographical conditions responsible for the dynamic processes, he fell back on the geological periods. And Glinka (19) justly states: "When one speaks of geographical position he understands the existence of a natural relation between the present distribution of climatic elements and the present geography of the soil cover. The regionality as described by Richthofen has at times no connection with the present climatic conditions. Thus the regions of glacial denudation, accumulation, river denudation, abrasions, and of volcanic transport exist on the surface of the earth entirely independently of the present climatic conditions." Richthofen, as well as Walther (72) who continued to develop the ideas of the former (51) considered the distribution of soils not from the standpoint of their origin but from their position. For this reason the "soil as natural historical body" was interchangeable in their scheme with geological material of soils, which eventually would be converted into soil as a natural body. It is this point which distinguishes Dokuchaev's views as a unique contribution which was later developed by other Russian soil scientists.

Dokuchaev as a trained geologist started out with the geologic point of view on soils current in those days. As soon as he came in contact with the vast stretches of Russian chernozem his keen eye immediately noted the homogeneous character and features (morphology) of the soils in a definite geographic region. In 1877 (10) he stated: "Whether we admit that the southwestern portion of Russia was submerged under the sea in the beginning of the post-tertiary period, as some geologists think, or it was covered by glaciers, as other geologists think, or it was dry land, as still another group of geologists think, matters little. For us it is important that after this or the other of the given phenomena the upper layers of the soils were apparently subject to various processes due to weathering and to processes due to vegetation; both of these were instrumental in changing the upper horizon of the parent material to a greater or lesser depth. These parent materials which have undergone



changes by the mutual activities of air, water, and plants, I call soil." In 1879 (11, 12) Dokuchaev formulated his ideas on soils in general: "Soils are the superficial mineral and organic constituents, always more or less colored by the humus, which constantly manifest themselves as a result of the combined activity of the following agencies: living and dead organisms (plants and animals), parent material, climate, and relief."

The original views of Dokuchaev differ little from those of the Western European students of soils and of Hilgard in the United States, who appreciated the genetic relationships in soil formation. The genetic principle as the foundation of soil classification was known and used by other workers besides Dokuchaev. Thus Hilgard (21, 22) in his extensive studies of the soils of the United States could not help but notice the regularity of the distribution of soils under the various physico-geographical conditions of the country. Hilgard had therefore, the genetic approach, noting the relations of the various soils with the different natural conditions and factors of soil formation. He failed, however, to see soils in their morphologic constitution as a result of the soil forming processes. He appreciated the factors of soil formation, but failed to correlate them and build a system of soil classification based on the correlated factors. Of the factors of soil formation Hilgard emphasized the moisture factor.

In discussing the relations of soils to climate Hilgard (21) said: "Since soils are the residual product of the action of meteorological agencies upon rocks, it is obvious that there must exist a more or less intimate relation between the soils of a region and the climatic conditions that prevail, or have prevailed therein."

"Since water is the prominent agent in soil formation, it follows that the variations in its supply—in other words, the greater or less amount of rainfall—must affect materially that process." The logical consequence of such a viewpoint was Hilgard's broad division of soils into two large groups: arid and humid.

Fundamentally the parent rock was the starting point of Hilgard's elucidation on soil characters and features, and in this respect he may be considered as an adherent of the geologic school of soil science.

The geologic point of view predominated in the work of the other early American students of soils. Thus Shaler (54) in his splendid monograph treats the subject of soils from the geologic point of view. To him soil is "a mixture of decayed rock and organic matter." Johnson (25) simply states that "soils are broken and decomposed rock." King (26), one of the keenest of American soil students, also had the geologic point of view.

There is a lot of material on the history of the subject in the reports of the geological surveys of the states and in the reports of the different agricultural societies in the United States. A partial list of references may be found in No. 13 Bibliographical contributions, U. S. Department, Agriculture Library, published in 1927.



The far reaching effects of Dokuchaev's later views (13, 14) consisted "*in excluding soils from the system of surface cover formations and placing them into a distinct independent system of natural science.*" [Quoted from Afanasiev (2).] For Dokuchaev soil science is just as distinct a science as botany, zoology, or any other of the natural sciences. This view was an outgrowth of his original thesis that "soil is an independent, natural, historical body." The factors of soil formation determine the type of soil in its genetic construction as manifested in the profile. "If we know the factors of soil formation we are able to state in advance what the soil must be like." This was one of the theses in the summary of Dokuchaev's doctor's dissertation.

One of Dokuchaev's collaborators, disciples, and followers was Sibirtzev. Indeed, some Russian soil investigators designate the Russian school of soil science as that of Dokuchaev and Sibirtzev. These two are considered as the founders and creators of the new school.

According to Sibirtzev (57, 59): "Under the term 'soil' we agreed to include what is known as the surface horizons of the parent material, in which the general dynamic processes are related to the biological processes. The variation in soils is determined: (a) by the parent material, i.e., its physico-chemical properties and position in space; (b) by the organisms, i.e., their kind, number, activity, and chemical transformations, resulting from it; and (c) by the physico-geographical conditions prevailing in the region during the process of soil formation and in their present final state." Sibirtzev considered moisture as the primary climatic factor in soil formation. In this his views coincide with those of Hilgard. He states [I am quoting from Glinka (19)]: "More important than the temperature is the humidity of the climate. Elsewhere enough was said about the primary and manifold influence of moisture on mechanical as well as chemical weathering. It is quite clear that in any isothermic belt the weathering of rocks varies (qualitatively and quantitatively) with the moisture conditions." In speaking of the climatic conditions in North America he stated: "The humidity conditions of the American climate change in an entirely different direction from those of European Russia: the loss in moisture does not follow the northwest-southeast direction, as in the southern half of European Russia, but the east and west. The eastern states are humid; the precipitation is twice as high as in our southern provinces. The western states, on the other hand, are very dry and are known among the Americans by the very inappropriate name 'arid region.' Correspondingly goes the distribution of soils."

It will be of interest to quote at this point the views of Sibirtzev (58) as to why the new concept of soils did not develop in the west [I am quoting from Afanasiev (2)]: "The causes which impeded the independent scientific study of soils in the west, and prevented the establishment of a genuine genetic classification of natural soils, were local, more or less accidental, due to external conditions, and were by no means of an essential nature."

"West-European scientists were less fortunate in this, for in most cases

they had to deal either with feebly developed soils, mixed with various geological deposits of inconsiderable thickness, or with eroded soils; and besides the soils have appreciably changed through cultivation.

"The methods of intensive and deep cultivation of the soils in the west, leaving out of consideration the introduction of various fertilizers, make them an artificially loosened mixture of natural soil material and of the underlying parent rock. The characteristic morphological horizons of the natural soil are either no longer or hardly distinguishable. The color and structure of the soil are altered and its composition tends to approach the composition of the parent material. Hence—the wide distribution of the geologico-petrographical and physico-chemical ideas on soil classification among the European scientists."

One of the prominent pupils of Dokuchaev was the late Dr. Glinka, whose volume on the distribution of soils—after having been translated into German—had a profound influence on the penetration of Dokuchaev's views into Germany and the United States.<sup>2</sup>

Glinka (19, 20), more than any of his predecessors, stressed the climate as a factor in the process of soil formation. He recognized, however, that in a number of cases the climatic factor may not be the predominating one and hence his divisions of *endodynamomorphic soils*, in which "the influence of the internal factors of soil formation (the properties of the parent material) definitely appears" and *ectodynamomorphic* in which climate as a factor in the process of soil formation is predominating.

We shall go no further in the historical development of Dokuchaev's ideas. Very new ideas developed on the concept of soil. The investigations of his followers deal to a great extent with soils as a natural body from the standpoint of soil classification. In this respect there is a wealth of material in the work of Nabokikh (42, 43), Visotskii (70), Tumin (67), Kossovich (27, 28), Sabanin (53), Neustruev (44), Dima (9), Vilenski (69), Kostichev (29), Gedroiz (18), and a great number of others. In this paper we are not directly interested in this phase of the work and leave it for an opportune moment. A summary of the classification schemes as an outgrowth of Dokuchaev's views may be found in the paper of Afanasiev (2) and in the volume of Glinka (19).

The review of the development of the concept "soil" in historical perspective would be incomplete without the mention of some of the other German satellites, like Liebig and Ramann. Liebig (31, 32), whose influence for a while overshadowed all other currents in soil science, fundamentally paid but little attention to soils as such. For him the soil was the test tube in which one may introduce the chemical ingredients necessary for plant growth. The chemical composition of the plant was the criterion by which he judged soils. In his famous Letters (32, p. 122) Liebig quotes the definition of soils given by

<sup>2</sup> Dr. Marbut, Bureau of Soils, U. S. Department of Agriculture, translated Glinka's volume: "The great soil groups of the world and their development," and it is obtainable in mimeographed form.

Gustav Walz (1857), director of the Agricultural Academy at Hohenheim, Stuttgart: "The soil consists of disintegrated rocks, and either rests upon these same rocks or on others elsewhere; the transported soil may, nevertheless, have remained the same and corresponds at least to the rocks from which it has its origin." Liebig the chemist, the exponent of the classical "mineral theory," considered soils as the storehouse of the chemical components supplied by the minerals found in the disintegration products of rocks.

Ramann (48, 49), however, had a definite outlook on the genesis of soils and in a way his ideas were similar to those of Hilgard, inasmuch as he also laid down climate as the important factor in the process of soil formation and divided soils according to degrees of humidity under which they exist. Ramann (48) states: "It is my wish that my paper on the problem, which the work of the modern Russian scientists has advanced still further, should be published first in your country, where soil science has attained so vast and independent a development. . . . The problem related to the origin of certain soil types due to the effect of climatic conditions, has been first studied by Russian scientists, and among them the names of Dokuchaev and Sibirtzev will forever be connected with the development of this branch of science."

#### *Modern definition of soils*

A definite step forward in the definition of soils has been made by Marbut (37), the prominent American representative of the Dokuchaev school. His definition is as follows: "*The soil consists of the outer layer of the earth's crust usually unconsolidated ranging in thickness from a mere film to a maximum of somewhat more than ten feet which differs from the material beneath it, also usually unconsolidated, in color, structure, texture, physical constitution, chemical composition, biological characteristics, probably chemical processes, in reaction and morphology.*"

The definition purports to convey the idea about soils in terms of soil characteristics instead of soil forming processes as defined by the great majority of the followers of the Dokuchaev school.

Some of the later Russian investigators had the same viewpoint as Marbut, and Kossovich [Kossowitsch (27)] one of the most prominent among them says: "The sum-total of the physico-chemical and biological processes which act directly in the soil and manifest themselves in various forms is the natural basis for grouping soils. . . . The construction of a soil classification on the basis of coördinating individual factors of soil formation (parent material, climate, vegetation, position of the soil, age, etc.) as such was carried out by Sibirtzev. This was a great step forward. *However, the classification of soils with any one factor alone as the basis does not seem to be promising. The genetic soil classification should be based on the internal properties and characteristics of the soil itself.*"

No definition of soils based on the internal characteristics of the soil is offered by Kossovich in this paper, but in his book (28) he does define soils:

*"All those surface horizons of the hard parent materials in which physico-chemical processes take place under the influence of the atmospheric agencies and in the presence of vegetation and animals."* It may readily be seen that this definition is not as comprehensive as that of Marbut.

It seems to the author of this paper that any definition which attempts to convey the idea of soils as "independent, natural body," which in turn places the science of soils on the same level as the other natural sciences, should embody this statement. There is another point in connection with the definition of Marbut which one may take exception to, and that is the embodiment of the geologic concept "the outer layer of the earth's crust." It is not the "geologic concept part" that one may object to, but the sense of the phrase designating as soil the "outer layer of the earth's crust." The term "outer layer" may be synonymous with the term "surface layer" and our knowledge of soils as a natural body tells us that we may have soils not only in close relation to the surface but even below the surface. We have reference here to the buried soils studied by Visotzkii (70), Nabokikh (43), Florov (17) and others. These soils preserved their distinguishing characteristics and are distinct and well-defined soils when analyzed from the viewpoint of soils as a natural, historical body. A study of such soils may reveal the conditions under which the overlying soil formed. These soils may be studied as are other natural bodies buried in the earth's strata, such as fossils which gave rise to the science of paleontology. Similar to paleontology in geology we may have a branch of soil science which should deal with buried soils and name this branch as *palepedology* or *paleoedaphology*, if the term edaphology is to be substituted for pedology as suggested by Shaw (55). Paleopedological studies of so-called fossil soils may reveal a lot of interesting geological data pertaining to climate.

Brevity of any definition is a desirable feature and it seems to the author that in Marbut's definition the clause: "ranging in thickness from a mere film to a maximum of somewhat more than 10 feet" may be omitted and instead the phrase "variable depth" substituted. As it stands there is an element of arbitrariness, which is not at all suggestive of the concept "soil."

The designations: "color, structure, and texture" may be omitted, since these are nothing more than some of the many other physical and morphological characters of soils. The words "probably chemical processes, in reaction" may also be omitted. The fact that the definition states the "chemical composition" (it should also include "properties") of the soil differs from that of the parent material implies a difference in chemical process. It is also clear that chemical properties of soils include, if anything, the reaction and the words "in reaction" are therefore not essential. With these explanatory remarks the definition of soils in terms of soil characteristics as suggested by Marbut (37) may be as follows: *The soil is a natural, historical body, of mineral and organic constituents, usually unconsolidated, of variable depth, which differs from the body of parent material below, also usually unconsolidated, in morphology, physical properties and constitution, chemical properties and composition, and*

*biological characteristics.* The introduction of the phrase "of mineral and organic constituents" in the definition seems to be justified on the ground that the combination of these constituents is the outstanding characteristic component of any soil.

The author is aware that there may be some loopholes in the modifications of Marbut's definition and the definition is presented here at this time with the hope that it might stimulate some other comments and result finally in a comprehensive logical and scientific definition of soils.

The discussion of the definition of the term "soil" would be incomplete without the mention of the one suggested by Shaw (55) in his comprehensive glossary of terms used in soil literature. It reads as follows: "The soil is a natural body occupying the surface portion of the earth, composed of mineral and organic materials and having more or less definitely developed horizons of eluviation and illuvation." The definition is accompanied by an explanation: "This term 'soil,' as defined, includes both the solum and the upper portion of the parent material, the A, B, and C horizons." The explanation as a support to the definition indicates the incompleteness of the definition, which in itself should be inclusive.

The definition as it stands does not convey the sum-total of soil characteristics. It is based on the characteristics of two horizons: eluvial<sup>3</sup> and illuvial. And how about the "gley," the zone of effervescence? Why then include just two characteristics to the exclusion of others?

It has been pointed out that the fact of the usual location of the soil on the surface of the earth does not define soils; it is not a soil characteristic. An oak on the surface of the ground or buried in some geologic strata is an oak just the same. A soil, if buried, as long as it retains its soil characteristics is a soil just the same. Afanasiev (2) one of the leading Russian soil geographers and taxonomists considers the great service of Dokuchaev's views as consisting "in excluding soils from the system of surface cover formations and placing them into a distinct independent system of natural science (see p. 45)."

### *Morphology of soils*

With the development of the scientific appreciation of soils, the methods of studying them have undergone radical changes, have been perfected and broadened. In the early history of soil science the viewpoint prevailing at the time determined the method of studying soils. Thus during the period of the geologic view the petrographic and mineralogical make-up of the soil was of primary importance. The agronomic point of view sought the mysteries of chemical reactions in the soil. Neither one of the soil science schools took

<sup>3</sup> The term "eluvial" in connection with the A horizon, as the horizon of eluviation "from which material has been removed," is not altogether satisfactory. We must remember that hand in hand with the process of removal there is a process of accumulation also in the A horizon: the mineralization of the organic matter and humus accumulation.

up the systematic study of soils as they are and for this reason the logical approach to the study of any object; namely, its appearance, features, and general characters, in short the morphology of soils, had to wait until the science of the soil had been recognized as an independent science.

It is, therefore, natural that this phase of soil science should have developed first of all in Russia.

The first one to apply the morphological method in the study of soils, according to Zakharov (76), was Ruprecht (52), but the method has been developed by Dokuchaev and his pupils. Those who are interested in the historical aspect of the development of soil morphology may find an excellent review in the English paper of Zakharov (75), probably the most prominent morphologist among the Russian soil scientists living.

It was the new concept of soils as an independent, natural, historical body which required not only the description of the surface features of soil but also the anatomy of it; for this it is necessary to cut a vertical section and thus obtain a profile view of the exposed vertically dissected body. In this manner the morphology of soils is being studied.

From a morphological point of view the soil is a body definitely organized with a definite mode of construction, or build. It consists of a series of genetically related horizons formed from the parent material, with the aid of organic residues. As expressed by Tumin (67): "a soil may be looked upon as a body with a genetic complex of horizons formed in the process of humification and humus fixation." The morphological type of the soil imparts certain specific characteristics to the construction and constitution of the horizons; each type, so to speak, has a constant orderly system of relationships within the profile between the horizons. Thus in the zone of podzol soils there is a definite type of soil construction; the profile features are: under the dark leaf-mold layer we find a light gray horizon known as  $A_1$ , followed by a lighter gray horizon  $A_2$ , under which we find a darker horizon B, into which substances from the upper horizons are washed (mechanically and chemically), and under this horizon the parent material designated as C, is located.

Within each zone<sup>4</sup> of soil formation the particular morphological type may develop on various kinds of parent material; we may therefore have podzols (a morphological term) on loess, on loam, on sands, etc. (mechanical and chemical composition and properties). And even within each morphologic type on a particular homogeneous parent material there may be subdivisions which manifest themselves in the soil construction. We may have at the border line

<sup>4</sup>The division of soils into zones was original with Sibirtzev (57). It is based on the soil formation processes within a geographical region. In Russia these zones run parallel with the climatic belts. Thus the Russian workers separate European Russia and Siberia into: Tundra zone in the north; in the northern part of the temperate belt there is the podzol zone, followed by the forest steppe zone, then the chernozem zone, chestnut, and the gray-arid desert zones. The zonal divisions have been investigated by other workers, and the work of Afanasiev (1) is the outstanding contribution on the subject.



of the zonal belts intrazonal groups, in which the podzolization, for example, may not be well developed. This gives rise to a class of podzolized (not true podzols) soils. The leached grayish white horizon so characteristic for podzols is not very pronounced in podzolized soils. The general features of the podzolized group are, however, true to the morphological type of podzol soils.

The difference in the make-up of the horizons is the feature which determines the class or group in the morphological type.

According to Zakharov (75) the construction or make-up of a soil profile gives us three or four distinct genetic horizons: (a) The decomposition-organic accumulation; (b) eluvial; (c) illuvial, and (d) parent material immediately below the illuvial horizon. These horizons are indicated by the first letters of the alphabet, but there is no uniformity in assigning any one particular letter to the respective horizons. Thus Zakharov designates the horizons by A, B, C, and D. Other Russian investigators consider as A any horizon or subhorizon from which material is being washed down mechanically or chemically; B as the horizon of accumulation, compaction, and deposition; and C as the parent material. This latter designation seems to have become popular also among the few investigators on the continent and in the United States.

Stremme (65), one of the prominent representatives of the Dokuchaev School in Germany, credits Orth (47) as having been among the first to study the soil profile. By stretching the point one may agree with Stremme, but the facts of the case are that Orth studied the surface and subsurface of soils and subsoils. He noted the differences in the layers and pointed them out, but this does not mean a study of the profile in the genetic relationships. Such studies as those of Orth were made by many other early soil investigators of the geologic and agronomic school in Europe and the United States.

In recent years the Russian genetic school of soil science has been adopted by a great number of soil workers. The international soil conferences held in Budapest (1909), Stockholm (1910), Prague (1922), Rome (1924), and finally the First International Congress of Soil Science held in Washington (1927) firmly established the validity of the profile studies.

In the United States and Canada some studies on the soil profile have been made, but the outstanding contribution in this field has been made by Marbut (33, 34, 35, 36, 37, 38). In 1921 (34) the first survey was made in which the profile of the soil was described; and in making the report of the survey Marbut (34) justly states, "This report marks a definite step forward in soil study." It was the pioneer work of Marbut that established the study of the profile in the United States and Canada.

Joel (23) discusses the soil profile as a basis for classification and applies the soil profile idea to the soils of Canada. With climate as the basis of major grouping he divides the soils into sub-humid-arid and humid, pointing out the differences in profile characteristics. Fundamentally this mode of division is similar to that expressed by Hilgard, as previously discussed. There is, however, the changing viewpoint with respect to the appreciation of genetic

horizons. This viewpoint is an incomplete simile of the zonal idea developed by Sibirtzev and Afanasiev as shown before.

The profile studies of peat by Dachnowski (6, 7) may be mentioned, but these offer little for the orientation in the profile structure of soils. It is questionable whether one should apply the term horizon, as viewed by the genetic school of soil science, to peat layers. Peats in most cases are geological deposits, and one may speak of peat deposits but not of soil deposits. Peat layers are not a result of an internal arrangement due to a definite type of soil forming process.

A profile study in the podzol soil zone was made by Wheeting (73). A number of interesting points were brought out by the analyses of some of the physical and chemical properties of the horizons in the profile.

McCool, Veatch, and Spurway (39) report some physical and chemical studies on the profiles of some Michigan soils; McCool and Weidemann (40, 41) report further studies on soil profiles. The title of one of these papers (40) is misleading and really does not in any way touch upon the subject of the soil profile. A study of the profile of forest soil in relation to reaction has been reported by Spokes (61). From this paper it is not clear how the horizons in the profile have been determined. The distribution of nitrogen in the profile of podzol soils has been studied by Edington and Adams (15). Other recent papers dealing with certain phases of the subject are those of Lebedev (30), Norton and Smith (46), and Spurway and Austin (63). Holmes (24a) studied the colloidal properties of several profiles on a silt loam soil.

A series of papers on soil profile studies appeared in the Proceedings and Papers of the First International Congress of Soil Science. Of these the paper by Joel (24) is of interest. It takes up the profile study within the several zones of soil formation; the few chemical analyses presented illustrate the validity of the field studies when made from the morphological standpoint. The micro-relief and origin of parent material introduce within any one zone patches of soil which should belong to a different zone. This has been pointed out by Tumin (67), Kossovich (27), and others.

A very instructive paper is the one by Baldwin (3) on the gray-brown podzolic soils of the eastern United States. A description of some soil profiles in Illinois is given by Norton (45). He attempts to establish a correlation between topography and drainage on the one hand and some soil characters on the other. Shaw (56) sketches the profile development in the secondary (immature) soils of California. Smolik (60) describes and gives the analyses of podzol soils in Czechoslovakia with special reference to the composition and behavior of the eluvial and illuvial horizons. Dachnowski-Stokes (8) makes an interesting comparison between peat profiles and peat soils. He rightly designates as layers or strata (a geologic concept) the profile constitution of peat; whenever the peat has been worked over by the forces of soil forming processes, become humified and mineralized as a result of which an



organic soil is formed with peat as the parent geologic material, he uses the term horizon in designating the profile constitution.

A valuable contribution to the study of the podzols is the paper by Veatch (68); it gives a clear picture of the soil forming processes in the region described. The paper of Wyatt and Newton (74) would have been more valuable if the chemical data included the aluminum and iron content of the soils described and illustrated.

The profile of the unique Cuban soils are lucidly described by Bennett (4). A reaction study of the soil profile in some Oregon soils is presented by Stephenson (64). The profile study of the microbial flora in Iowa, by Brown and Benton (5a) should be mentioned.

A large number of papers on the subject of the soil profile appeared in Russia. A review of only those which have appeared in recent years would necessitate a separate paper. The originals of these papers are in a large number of cases not accessible and besides most of these papers deal with profile studies of the various soil zones from the standpoint of soil classification. As the latter point is not the object of this review, it was deemed advisable to leave the papers out for a more opportune occasion.

The study of the soil profile is at present an indispensable part in any branch of soil science. The soil morphologist, the soil surveyor, the physicist, the chemist, the microbiologist, even the agronomist, all have turned their attention to the soil profile, its constitution and its make-up in horizons, for the study of soils as a natural, historical body is possible only upon exposing the body in its cross-section, which is the same as the profile.

The methods used in the study of the profile of some New Jersey soils and some of the results will be the subject of a forthcoming paper.

#### SUMMARY

1. A discussion is presented on the development of soil science as an independent science.
2. The ideas on soil and the various schools of soil genesis are reviewed with special reference to the Russian school from the time of Dokuchaev to date.
3. The definitions of soil as given by Marbut and Shaw are critically analyzed and a modification of the Marbut definition is presented.
4. The suggestion is made to consider a branch of soil science to be known as paleopedology or paleoedaphology for the study of buried soil.
5. The soil morphology and the soil profile are discussed and a review of the subjects is presented.

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COMPOSITION OF NATURAL ORGANIC MATERIALS AND THEIR  
DECOMPOSITION IN THE SOIL: IV. THE NATURE AND RAPID-  
ITY OF DECOMPOSITION OF THE VARIOUS ORGANIC COM-  
PLEXES IN DIFFERENT PLANT MATERIALS, UNDER AEROBIC  
CONDITIONS

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The rapidity of decomposition of different organic substances of either plant or animal origin in soil is controlled largely by four distinct factors:

(a) The chemical composition of the organic material, which, in the case of plants and plant remains, depends primarily upon the nature and age of the plant as well as upon the conditions of its nutrition. (b) The presence of sufficient nitrogen to enable the microorganisms bringing about the decomposition to carry out this process in the shortest possible time; in the case of nitrogen-rich plant residues, as in young plants used for green manuring purposes, or legume residues, this never becomes a limiting factor; however, in the case of plant residues poor in nitrogen, such as straw, the problem may become one of considerable importance. (c) The nature of microorganisms active in the decomposition processes. (d) The environmental conditions at which decomposition is carried out, especially aeration, moisture supply, soil reaction, and temperature.

To throw light upon these important phases of the problem of decomposition of organic residues in the soil, the following experiments were undertaken. Four different plant materials, varying distinctly in chemical composition, were selected for this purpose; namely, (a) mature corn stalks (and leaves); (b) rye straw; (c) mature, yellow oak leaves, freshly fallen to the ground; (d) mature alfalfa plants, freshly harvested.

Each of these plant materials was collected in sufficient quantity and passed separately through a chopper, which cut them into small pieces. After the moisture content of the plant material was determined, a sufficient quantity of each was added to a series of glazed earthenware pots, to give 200 to 280 gm. of dry material in each pot. Sufficient water was then added to each pot to bring the total moisture content of the compost to 66.6 per cent, or to 200 per cent moisture on the basis of the dry organic matter.

Half of the pots received a mineral solution containing 1 gm.  $(\text{NH}_4)_2\text{HPO}_4$ , 1 gm.  $\text{K}_2\text{HPO}_4$ , and 2 gm.  $\text{CaCO}_3$ . The nutrients thus added were far from sufficient to allow a very rapid decomposition of the nitrogen poor plant materials, such as the rye straw; at least five times as much additional nitrogen would have been required by the microorganisms for the complete decomposition of the celluloses and hemicelluloses in this plant material. All the pots

were inoculated with a suspension of fresh soil, covered with plates, and incubated at 25 to 28°C.

At intervals, the residual organic matter in each pot was weighed, the moisture content determined, and an aliquot portion taken for analysis. The results were always calculated on the basis of both the percentage of the residual material and the total original material, making thereby due allowance for the samples removed at different times for chemical analysis; the last calculation would enable one to determine just how much of the total amount of each of the different plant constituents had been decomposed in the given period of time.

Various methods have been used in the past for following the course of decomposition by microorganisms of plant material or animal residues, either in soil or in compost. These methods were usually based upon measuring only one product of decomposition, such as ammonia and frequently nitrate or carbon dioxide. The assumption was thereby made that under a definite set of conditions, the liberation of these various products of microbial metabolism runs parallel to the total decomposition of the organic residues as a whole as well as of their various constituents. This assumption is not always justified. In the case of a plant substance containing only a small amount of nitrogen, very little free ammonia or nitrate will be produced even after considerable decomposition has taken place. This is because most of the inorganic nitrogen, which becomes liberated as a result of the decomposition of the organic nitrogenous constituents of the plant substance, is reassimilated by the microorganisms; the latter utilize the energy liberated in the process of decomposition of the celluloses and hemicelluloses. Evolution of carbon dioxide is a more direct index of decomposition, although the disintegration of the same amount of cellulose will yield varying amounts of carbon dioxide when carried out by different organisms and under different conditions. Further, this method tells nothing at all as to the particular chemical complexes among the plant constituents which are undergoing decomposition. To speak of the decomposition of the plant material as a whole, as measured by the evolution of carbon dioxide, is to neglect the nature of the numerous chemical processes which are taking place thereby. Another important limitation of these methods for studying decomposition of organic matter is that little information is gained concerning the chemical nature of the residual material which results from decomposition and which goes to increase the "humus" content of the soil.

Attempts have been made in some instances to measure the decomposition of plant material either by determining the total reduction in the bulk of the organic matter or by measuring the disappearance of one of the important constituents. However, the mere fact that 40, 60, or 80 per cent of the organic matter of the specific plant material has disappeared, under certain conditions of decomposition and in a definite period of time, supplies no in-



formation whatsoever concerning the chemical changes that have taken place in the various constituents.

Studies dealing with the disappearance of specific chemical complexes in the organic material undergoing decomposition have been limited largely to the celluloses and hemicelluloses. Barthel and Bengtsson (2) have shown that the decomposition of celluloses in plant residues depends upon the nature of the plant and upon the amount of available nitrogen. Cellulose in the stubble and roots of legumes decomposed more slowly than did cellulose in the roots of cereal straws. This was explained by the greater content of nitrogen-free, non-cellulosic, carbonaceous materials in the former than in the latter. Fraps (5) observed that, as a result of decomposition of different plant materials in soil for a period of eight weeks, there were left 7 per cent of the pentosan in cotton seed meal, 31 per cent of the pentosan in Sudan grass, 61 per cent of the pentosan in rice bran, and 75 per cent of the pentosan in sheep manure. These results point definitely to differences in the decomposition of the same group of organic complexes in different plant materials.

Schmidt, Peterson, and Fred (11) found that when corn fodder and rye straw were undergoing decomposition under the same conditions, the former lost 50 per cent of its pentosans in 100 days and the latter only 35 per cent in 300 days; they also observed that common fungi synthesize pentosans, even in media free from pentose material. According to Rege (9), 80 per cent of the pentosan in fresh rye straw, when the straw is allowed to decompose under favorable conditions, disappeared in 40 days; in fact during the early period of decomposition, that is between the fourth and eighth days, practically all the loss in dry matter was accounted for almost entirely by the loss of pentosan.

Very few attempts have been made to measure the rate of disappearance of the various chemical complexes in the decomposing plant materials. The investigations of Egorov (6), Bach (1), and König (7) can be summarized as follows: During the early stages of decomposition of plant materials in soil or in compost, the pentosans disappear more rapidly than do the total organic constituents of the material, and even more rapidly than do the celluloses. After considerable decomposition has taken place, the celluloses are found to disappear more quickly than the hemicelluloses (including the pentosans). The rate of decomposition of both hemicelluloses and celluloses is greater than that of the total organic matter, as shown by the amount of residual material. Organic nitrogenous compounds tend to accumulate, especially in the case of nitrogen-poor organic residues, so that the total protein content of the residual undecomposed material diminishes only slowly when compared with the rate of disappearance of the total organic matter. Lignins seem to be resistant to decomposition, more so than any other group of the major plant constituents; they are found, therefore, to accumulate in the process of decomposition of plant residues, with certain few exceptions.

Bach (1) found that when stable manure is added to the soil and allowed to decompose, the per cent of carbon in the residual organic matter increases



from an initial 47 to 51 per cent to 58 per cent. This was explained by the fact that the celluloses and pentosans originally present in the fresh manure contained 44.44 and 45.44 per cent of carbon respectively, while the lignins and cutins contained 67.31 to 71.35 per cent of carbon. As a result of decomposition, the celluloses and pentosans disappear rapidly while the lignins and cutins accumulate, thus leading to a gradual increase in carbon content.

Rose and Lisse (10), analyzing wood at different stages of decomposition, and Bray and Andrews (3) working with pure cultures of fungi, also demonstrated that, in the decomposition of wood by various Hymenomycetes, the pentosans and celluloses are first to disappear, whereas the lignins are practically resistant to decomposition. Only very few fungi, namely those causing the "white rots," are capable of decomposing lignins as well as celluloses (4). The common wood-destroying fungus *Merulius lacrymans* decomposes the celluloses while the lignins are left; these are converted partly into depolymerized and split substances of a "humin-like" nature.

It has also been found that, as a result of the decomposition of plant substances there is a marked increase in the alkali-soluble material of the undecomposed or accumulated residues. The tendency has been to explain this phenomenon either by a modification of the lignin molecule, making it more readily soluble in alkali, or by the formation of some intermediary products of cellulose decomposition soluble in alkalies.

Waksman and Tenney (14) came to the conclusion, as a result of studies on the decomposition of the rye plant harvested at different stages of growth, that the water-soluble organic substances are first to be decomposed in the soil by microorganisms. This is soon followed by an attack upon the pentosans and at the same time, or immediately after, upon the celluloses. Although the plant residues contain a larger amount of celluloses than of hemicelluloses and although the latter begin to undergo decomposition sooner than the former, the celluloses disappear sooner and more completely than the hemicelluloses. This was explained by the fact that, whereas pentosans may be attacked more quickly and by a greater variety of microorganisms than celluloses, other hemicelluloses (galactans, mannans) may be more resistant; further, as a result of the growth of microorganisms upon the plant residues, considerable quantities of hemicelluloses are synthesized in the form of bacterial and fungus slimes and gums. The lignins were found to be more resistant to decomposition and tend to accumulate in the soil. The plant proteins are readily decomposed, but very little nitrogen becomes liberated in the soil as ammonia, as long as there is left a considerable amount of undecomposed cellulose and pentosan. Accompanying the decomposition of these carbohydrates, considerable synthesis of microbial proteins takes place. This synthesis is also a result of the growth of the microorganisms bringing about the decomposition of the organic matter.

The dark residues resulting from the decomposition of the plant material, or the so-called "humus" tends to have the following composition: a large

amount of lignins or modified lignins of plant origin; a large amount of protein of microbial origin; a fairly high hemicellulose content, partly of plant and partly of microbial origin; small amounts of plant constituents still undergoing decomposition, such as celluloses and ether-soluble substances; small amounts of other synthesized microbial products, some of which are undergoing decomposition, as various fatty substances, chitinous materials and nitrogenous complexes.

An attempt will be made in this paper to elucidate the problem of decomposition of different plant materials under aerobic conditions, to establish the relation between the different organic plant constituents in the process of

TABLE 1  
*Proximate composition of plant materials used for decomposition studies*  
On per cent basis of dry material

CHEMICAL CONSTITUENTS	CORN STALKS	EYE STRAW	OAK LEAVES	ALFALFA PLANTS
Ether-soluble fraction.....	1.80	1.84	3.71	2.75
Cold-water-soluble.....	10.58	4.51	8.28	12.44
(Reducing sugar).....	(6.00)	(0.88)	(2.73)	(1.31)
Hot-water-soluble.....	3.56	1.75	5.65	4.80
(Alcohol-soluble*).....	(4.19)	(3.49)	(5.92)	(7.66)
Hemicelluloses.....	17.63	21.10	12.93	8.52
Celluloses.....	29.67	38.62	13.78	26.71
Lignins.....	11.28	14.63	30.30	10.78
Crude protein.....	1.98	0.81	4.25	8.13
(Total nitrogen).....	(0.66)	(0.24)	(0.77)	(2.58)
Ash.....	7.53	4.18	5.09	10.30

\* The alcohol-soluble fraction was determined on a separate sample. In view of the fact that this fraction was not determined in the decomposed material, it is left out of further consideration; it is given here, however, merely for the purpose of comparison.

decomposition, and to throw further light upon the rôle of microorganisms in the processes of decomposition and synthesis.

It is quite essential, in a study of this nature, to be able to make as complete an analysis of the organic plant constituents as possible. Such an analysis has been proposed elsewhere (12) and was used to considerable advantage for determining the proximate composition of various plant materials. It was found that, by this method of analysis, 85 to 96 per cent of the plant constituents (except in the case of mosses) could be accounted for. No attempt has been made to measure those complexes which occur in the plant in concentrations of less than one per cent.

The following organic complexes are accounted for in this method:

(a) cold-water-soluble substances, including the sugars and amino acids; (b) hot-water-soluble substances, including starches, pectins, tannins, and uric acid; (c) hemicelluloses, determined by hydrolysis with hot dilute mineral acid and measured in the form of reducing

sugars; (d) celluloses, determined by hydrolysis with cold 80 per cent sulfuric acid followed by boiling for several hours, after diluting with 15 volumes of water; (e) lignins, as determined by their insolubility in cold 80 per cent sulfuric acid, with ash and nitrogen accounted for; (f) ether-soluble substances, including fats and waxes; (g) crude proteins.

In view of the fact that the alcohol-soluble fraction is not included in the following analyses, the results will be short 3.5 to 7.5 per cent of the plant constituents. However, since the same method has been used in the analysis of both the fresh material and the decomposed residues, the results are found to be comparable. The proximate chemical composition of the four materials used in the following investigations is given in table 1. The corn stalks were harvested when mature but not fully dry, some of the leaves being still green. The rye straw was in a fully mature stage, as shown by the low nitrogen

TABLE 2  
*Chemical composition of corn stalks and decomposed residue at different stages of decomposition, without the addition of nutrient salts*  
On per cent basis of dry material

CHEMICAL CONSTITUENTS	ORIGINAL PLANT MATERIAL	AFTER DAYS OF DECOMPOSITION			
		27	68	205	405
Ether-soluble.....	1.80	1.97	0.96	0.78	0.35
Cold-water-soluble.....	10.58	3.37	5.74	2.80	4.28
Hot-water-soluble.....	3.56	2.50	3.02	4.11	9.19
Hemicelluloses.....	17.63	16.34	15.93	15.35	10.74
Celluloses.....	29.67	26.36	22.50	13.39	4.78
Lignins.....	11.28	18.26	19.66	23.44	23.86
Crude protein.....	1.98	4.37	4.69	9.00	12.97
Ash.....	7.53	.....	.....	19.16	26.63

content. The oak leaves were also mature and recently fallen; they were collected from the surface of ground under the trees. The alfalfa plants were freshly harvested in the fall of the year.

Attention should be called to the fact that the crude protein figures indicate the total nitrogen minus the water-soluble nitrogen, the difference being multiplied by 6.25. The total nitrogen figures are given separately.

#### DECOMPOSITION OF CORN STALKS

The corn stalks contained 66 per cent moisture when harvested, showing that they were not as yet fully mature. The material was air-dried and subjected to a detailed chemical analysis, the results of which are given in table 1. For the study of aerobic decomposition, the fresh material was cut up immediately and used without preliminary drying. In view of the fact that the moisture content of the fresh material was just sufficient for optimum aerobic decomposition, no more water was added. The analysis of the dry material shows that it contained 10.58 per cent of organic substances soluble

in cold water. More than half of this, namely 6 per cent, was in the form of reducing sugars. This high concentration of sugar explains the rapid initial decomposition of the corn stalks. Out of the 0.66 per cent total nitrogen in the dry material, 0.26 per cent, or nearly 40 per cent of the total nitrogen,

TABLE 3

*Chemical composition of corn stalks and the decomposed residue at different stages of decomposition, in the presence of added nutrient salts*

On per cent basis of dry material

CHEMICAL CONSTITUENTS	ORIGINAL PLANT MATERIAL	AFTER DAYS OF DECOMPOSITION			
		27	68	205	405
Ether-soluble.....	1.80	2.22	0.80	0.64	0.25
Cold-water-soluble.....	10.58	3.43	5.27	3.96	4.59
Hot-water-soluble.....	3.56	2.45	3.20	5.36	8.71
Hemicelluloses.....	17.63	15.56	16.41	10.68	10.39
Celluloses.....	29.67	23.80	21.93	6.28	5.05
Lignins.....	11.28	17.70	19.12	23.83	21.30
Crude protein.....	1.98	4.81	6.84	10.93	12.13
Ash.....	7.53	.....	.....	26.12	29.43

TABLE 4

*Total decomposition of the various organic chemical constituents of corn stalks, without the addition of nutrient salts*

ORGANIC CONSTITUENTS	ORIGINAL MATERIAL	MATERIAL LEFT AFTER DAYS OF DECOMPOSITION							
		27		68		205		405	
		Total residue	Per cent of original	Total residue	Per cent of original	Total residue	Per cent of original	Total residue	Per cent of original
	gm.	gm.		gm.		gm.		gm.	
Total dry material.....	203.00	129.00	63.54	92.50	45.60	59.50	29.30	41.20	20.30
Ether-soluble fraction....	3.65	2.54	69.59	0.89	24.38	0.46	12.60	0.14	3.84
Cold-water-soluble organic matter.....	21.48	4.35	20.25	5.31	24.72	1.67	7.77	1.76	8.19
Hot-water-soluble organic matter.....	7.23	3.23	44.67	2.79	38.59	2.45	33.89	3.79	52.42
Hemicelluloses.....	35.79	21.09	58.93	14.74	41.18	9.13	25.51	4.42	12.35
Celluloses.....	60.24	34.00	56.44	20.81	34.55	7.97	13.23	1.97	3.27
Lignins.....	22.90	23.56	102.88	18.19	79.43	13.95	60.92	9.83	42.93
Crude protein.....	4.01	5.64	140.65	4.34	108.23	5.36	133.67	5.34	133.17

was in a water-soluble form. These facts, as well as the low lignin content of the corn stalks, account for the rapid disappearance of most of the organic constituents in their decomposition, especially in the presence of a small amount of inorganic salts of nitrogen, phosphorus, and potassium.

Tables 2 and 3 give the chemical composition of the corn stalks, with and

without the additional nutrients, at different stages of decomposition. Tables 4 and 5 show the amount of total decomposition that the various organic chemical constituents have undergone, in the absence and in the presence of added nutrient salts, as shown by the concentrations of the various groups left at the different periods of incubation. These figures were obtained by multiplying the total residual material (on a dry basis and after allowance has been made for the samples removed) by the percentage composition.

Figures 1 and 2 illustrate the rapidity of transformation of the most important groups of organic plant complexes, in the process of decomposition of corn stalks, with and without additional nutrient salts. The left hand columns represent the abundance of the particular complex in the original undecom-

TABLE 5  
*Total decomposition of the various organic chemical constituents of corn stalks in the presence of added nutrient salts*

ORGANIC CONSTITUENTS	ORIGINAL MATERIAL	MATERIAL LEFT AFTER DAYS OF DECOMPOSITION							
		27		68		205		405	
		Total residue	Per cent of original	Total residue	Per cent of original	Total residue	Per cent of original	Total residue	Per cent of original
	gm.	gm.		gm.		gm.		gm.	
Total dry material.....	203.00	107.30	52.86	83.20	41.00	53.80	26.50	45.70	22.50
Ether-soluble fraction....	3.65	2.38	65.21	0.67	18.36	0.34	9.32	0.11	3.01
Cold-water-soluble organic matter.....	21.48	3.67	17.09	4.38	20.39	2.13	9.92	2.10	9.78
Hot-water-soluble organic matter.....	7.23	2.62	36.24	2.66	36.79	2.88	39.83	3.98	55.05
Hemicelluloses.....	35.79	16.65	46.52	13.65	38.14	5.75	16.07	4.75	13.27
Celluloses.....	60.24	25.46	42.26	18.25	30.30	3.38	5.61	2.31	3.83
Lignins.....	22.90	18.94	82.71	15.91	69.48	12.82	55.98	9.73	42.49
Crude protein.....	4.01	5.16	128.68	5.69	141.90	5.88	146.63	5.54	138.15

posed plant material, on the basis of 100 per cent. The second column to the right of it represents the concentration, in per cent, of the particular complex at the time of the first sampling, namely after 27 days; the third, fourth, and fifth columns to the right represent the concentrations of the particular complex at the second, third, and fourth sampling; namely, after 68, 205, and 405 days, respectively.

Both the tables and figures give a fair idea of the processes which have been taking place in the decomposition of corn stalks under aerobic conditions. The addition of inorganic nutrients exerted a decidedly favorable effect upon the early stages of decomposition of the total organic matter, especially of the celluloses and hemicelluloses. After 27 days, 36.5 per cent of the total organic constituents of the corn stalks disappeared in the absence of the additional salts and 47.1 per cent in their presence; 41 per cent of the hemi-

celluloses and 43.6 per cent of the celluloses were decomposed in the absence of added nutrients, whereas, in their presence, the disappearance of these two groups of complexes was 53.5 and 57.7 per cent respectively. These results induce certain important conclusions: 1. The addition of available nitrogen was responsible for a greater decomposition of the celluloses and hemicelluloses in the corn stalks, especially during the early stages of decomposition. 2. Both the hemicelluloses and the celluloses disappeared more quickly than the total organic matter; this indicates either that synthesis of new complexes has taken

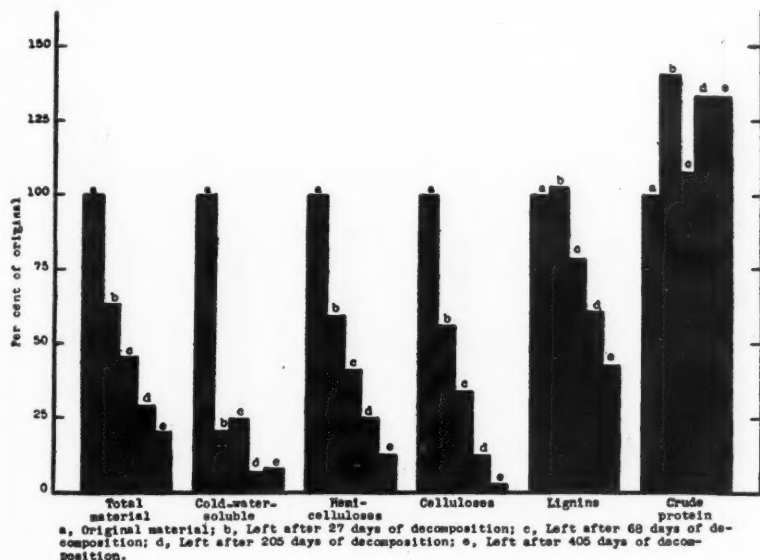


FIG. 1. DECOMPOSITION OF VARIOUS CHEMICAL CONSTITUENTS OF CORN STALKS WITHOUT ADDITIONAL NUTRIENT SALTS

place or that some of the more resistant plant complexes have accumulated. Both assumptions are correct, as is shown later.

The favorable effect of additional inorganic nutrients upon decomposition is still marked after 68 days of decomposition, but this effect tends to disappear later. It is interesting to note also that at the beginning of decomposition the hemicelluloses decomposed as rapidly as if not more so than the celluloses; however, during the latter stages, the celluloses disappeared rapidly, while appreciable quantities of hemicellulose were still left in the residual compost.

The cold-water-soluble substances tend to disappear rapidly when decomposition sets in. The hot-water-soluble constituents decompose more slowly and even tend to accumulate during the later stages of decomposition, no



doubt because of the production of synthesized microbial cell substance containing substances soluble in hot water. The fats and oils, or the ether-soluble substances, of the corn stalks were also rapidly decomposed under aerobic conditions.

The lignins and the proteins are the two important complexes among the various organic plant constituents which tend to accumulate. The reason for their accumulation, however, is not the same in both cases. The lignins are more resistant to attack by microorganisms than are the other groups of plant constituents, such as the celluloses, hence they accumulate as the decomposition

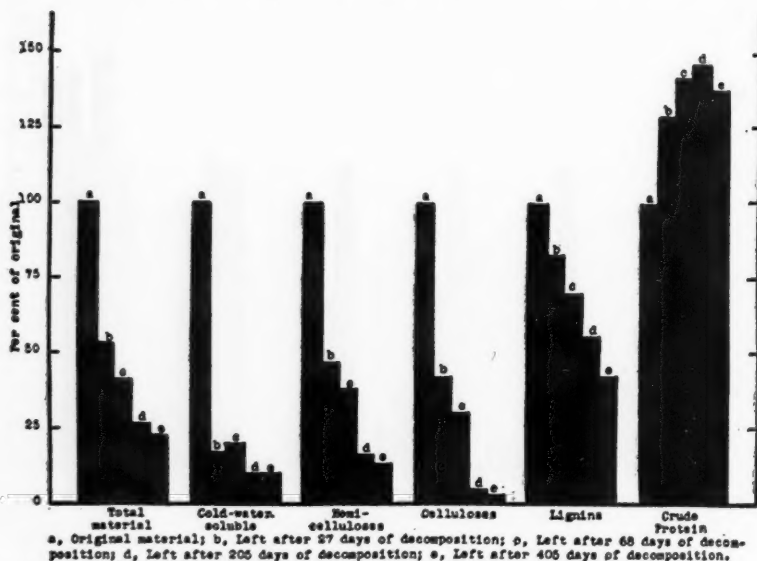


FIG. 2. DECOMPOSITION OF VARIOUS CHEMICAL CONSTITUENTS OF CORN STALKS WITH ADDITIONAL NUTRIENT SALTS

of the more readily available complexes proceeds further. In 27 days, only a small fraction of the lignins of the corn stalks undergoing decomposition under aerobic conditions has disappeared; this accounts for the increasing concentration of the lignin content of the residual material. The original plant substance had only 11.28 per cent lignin; the material decomposed for 405 days contained twice as much lignin in proportion to the other constituents. However, there was no absolute preservation of the lignin complex, as assumed by some investigators. Under aerobic conditions, the lignins gradually decompose, not so rapidly by far as the other chemical complexes, but still in a very definite manner; after 405 days, 57.5 per cent of the lignin in the corn stalks has actually disappeared. Under anaerobic conditions, the



lignins are preserved to a much greater extent, as will be shown in a later contribution.

These results as well as those obtained on the decomposition of the other three plant materials prove definitely that lignins decompose under aerobic conditions. So far no definite explanation can be submitted concerning the nature of the microorganisms active in this process. It is known that certain *Basidiomycetes* are capable of decomposing lignins in the rotting of trees. It is also known that lignins disappear partly when digested by animals; the limited evidence points to actinomyces as possible agents in the decomposition of lignins. Whether one of these three groups of organisms was responsible for the disappearance of some of the lignins in the decomposition studies reported here or all three groups of organisms took a part in the process still remains to be established.

TABLE 6  
*Nitrogen transformation in the decomposition of corn stalks*  
In per cent of total residual material

FORM OF NITROGEN	NO ADDITIONAL NITROGEN					AMMONIUM PHOSPHATE ADDED				
	Incubation					Incubation				
	0 days	27 days	68 days	205 days	405 days	0 days	27 days	68 days	205 days	405 days
Total nitrogen.....	0.66	0.95	1.02	1.70	2.44	0.76	1.05	1.37	2.10	2.34
Soluble in cold water.....	0.25	0.13	0.14	0.13	0.12	0.35	0.16	0.14	0.14	0.14
Soluble in hot water.....	0.09	0.12	0.13	0.13	0.25	0.09	0.13	0.14	0.21	0.26
Hydrolizable by 2 per cent HCl.....	0.13	0.23	0.36	....	0.92	0.13	0.28	0.39	....	0.93
"Humin" nitrogen, not acted upon by autoclaving with 6 per cent H <sub>2</sub> SO <sub>4</sub> ....	0.13	0.24	0.33	0.44	0.51	0.13	0.27	0.33	0.51	0.51

The increase in the crude protein (insoluble in cold and hot water) with the advance of decomposition of the corn stalks was not only relative to the other plant constituents, but there was an actual total increase in the amount of protein, due to the transformation of the water-soluble nitrogen compounds into insoluble complex organic nitrogenous substances. The greatest increase in the protein content was obtained in those preparations which received inorganic nitrogen salts. The reasons for the increase in the protein as a result of decomposition of nitrogen-poor organic plant residues have been expounded in detail elsewhere (15). These results throw further light upon the problem of synthesis of new protein material as a result of the activities of the microorganisms which bring about the decomposition of the celluloses and hemicelluloses. The fact that, in the absence of additional nitrogen, the increase in the amount of crude protein took place at the expense of the water-soluble simple nitrogenous compounds is brought out in table 6. Although the total nitrogen of the residual material rapidly increased with the advance

in decomposition, the water-soluble nitrogen decreased. The acid hydro-lizable nitrogen increased even more rapidly than the total nitrogen. It is interesting to record the marked increase in the so-called "humin" nitrogen or that part of the nitrogen which is found in the lignin fraction. These results point definitely to the building up of resistant nitrogenous complexes by the microorganisms.

As the water-soluble and insoluble nitrogenous compounds, first in the form of plant constituents then as constituents of microbial cells undergoing decomposition, are repeatedly hydrolyzed and resynthesized by microorganisms, more and more of the resistant nitrogenous complexes are produced. These are attacked less and less readily, and finally become incorporated in the residual material equivalent to the soil "humus" with its large content of organic nitrogenous complexes resistant to decomposition.

TABLE 7  
*Chemical composition of rye straw and its decomposition products at different stages of decomposition, without the addition of nutrient salts*  
On per cent basis of dry material

CHEMICAL CONSTITUENTS	ORIGINAL PLANT MATERIAL	AFTER DAYS OF DECOMPOSITION		
		66	143	386
Ether-soluble.....	1.84	1.05	1.33	1.62
Cold-water-soluble.....	4.51	2.12	2.45	1.75
Hot-water-soluble.....	1.75	2.19	2.23	2.08
Hemicelluloses.....	21.10	19.81	21.25	18.18
Celluloses.....	38.52	35.33	33.47	30.38
Lignins.....	14.63	17.53	17.59	18.88
Crude protein.....	0.81	1.69	1.88	2.76
Ash.....	4.18	5.50	5.60	5.72

#### DECOMPOSITION OF RYE STRAW

The chemical composition of the rye straw used in these decomposition studies varied in several respects from that of the corn stalks. The straw had much less water-soluble material, much less nitrogen, but a larger proportion of celluloses, hemicelluloses, and lignins. One would expect from this analysis that the decomposition of the straw should proceed at a much slower rate than that of the corn stalks. This was actually found to be the case.

The straw, undergoing decomposition under the same conditions as the corn stalks, was analyzed only three times; namely, after 66, 143, and 386 days incubation at 25-28°C. Tables 7 and 8 give the chemical composition of the straw without and with the same additional inorganic salts at different stages of decomposition. Tables 9 and 10 and figures 3 and 4 give the total corresponding amounts of the different chemical complexes of the fresh and decomposed material at the different stages of decomposition.

In comparison with the corn stalks, the rye straw was found to decompose very slowly. Although the nature and course of decomposition of the straw are similar to that of the corn product, the amount decomposed is considerably less. At the end of 386 days, nearly three times as much organic matter was left from the straw as from the corn stalks. This is due largely

TABLE 8

*Chemical composition of rye straw and its decomposition products at different stages of decomposition, in the presence of added nutrient salts*

On per cent basis of dry material

CHEMICAL CONSTITUENTS	ORIGINAL PLANT MATERIAL	AFTER DAYS OF DECOMPOSITION		
		66	143	386
Ether-soluble . . . . .	1.84	0.92	1.14	0.59
Cold-water-soluble . . . . .	4.51	2.05	2.21	1.76
Hot-water-soluble . . . . .	1.75	1.89	1.81	1.80
Hemicelluloses . . . . .	21.10	19.61	21.10	17.98
Celluloses . . . . .	38.62	33.58	31.02	25.99
Lignins . . . . .	14.63	18.10	18.28	18.43
Crude protein . . . . .	0.81	2.25	2.38	3.53
Ash . . . . .	4.18	6.50	6.50	8.00

TABLE 9

*Total decomposition of the various organic constituents of rye straw, without the addition of nutrient salts*

ORGANIC CONSTITUENTS	ORIGINAL MATERIAL	ORGANIC MATTER LEFT, AFTER DAYS OF DECOMPOSITION					
		66		143		386	
		Total residue	Per cent of original	Total residue	Per cent of original	Total residue	Per cent of original
	gm.	gm.		gm.		gm.	
Total dry material . . . . .	277.00	230.00	83.03	197.00	71.12	171.00	61.73
Ether-soluble fraction . . . . .	5.10	2.42	47.45	2.62	51.37	2.77	54.31
Cold-water-soluble organic matter . . . . .	12.49	4.88	39.07	4.83	38.67	2.99	23.94
Hot-water-soluble organic matter . . . . .	4.85	5.04	103.92	4.39	90.52	3.56	73.40
Hemicelluloses . . . . .	58.42	45.56	77.99	41.86	71.65	31.09	53.22
Celluloses . . . . .	106.66	81.25	76.18	65.94	61.82	51.95	48.71
Lignins . . . . .	40.51	40.32	99.53	34.65	85.53	32.28	79.68
Crude protein . . . . .	2.25	3.88	172.44	3.70	164.44	4.72	209.78

to the insufficient decomposition of the celluloses and hemicelluloses in the straw: at the end of 405 days there was left in the case of the corn stalks 3.27-3.83 per cent of the celluloses and 12.35-13.27 per cent of the hemicelluloses; however, in the case of the straw, there was left, at the end of practically the same period of time (386 days) 37.28-48.71 per cent of the celluloses and 47.09 to 53.22 per cent of the hemicelluloses present in the original material.

The lack of available nitrogen was chiefly responsible for the slow decomposition of the rye straw, especially of the celluloses and hemicelluloses. The amount of inorganic nitrogen added to some of the pots was not sufficient to produce conditions most favorable for decomposition of the straw. It resulted only in a somewhat greater reduction of both groups of carbohydrates than in the straw not receiving any additional available nitrogen.

Here also the lignins proved to be more resistant to decomposition than the other constituents of the straw. Likewise, the reduction in total organic matter was less than the decrease of celluloses and hemicelluloses. The total organic matter was reduced by 38.3 per cent in the absence of additional nitrogen and by 44.8 per cent in its presence. However, the celluloses were reduced by 51.3 and 62.7 per cent and the hemicelluloses by 46.8 and 52.9

TABLE 10  
*Total decomposition of the various organic chemical constituents of rye straw, in the presence of added nutrient salts*

ORGANIC CONSTITUENTS	ORIGINAL MATERIAL	ORGANIC MATTER LEFT, AFTER DAYS OF DECOMPOSITION					
		66		143		386	
		Total residue	Per cent of original	Total residue	Per cent of original	Total residue	Per cent of original
	gm.	gm.		gm.		gm.	
Total dry material.....	277.00	221.00	79.78	170.00	61.37	153.00	55.23
Ether-soluble-fraction.....	5.10	2.03	39.80	1.94	38.04	0.90	17.65
Cold-water-soluble organic matter....	12.49	4.53	36.27	3.76	30.10	2.69	21.54
Hot-water-soluble organic matter....	4.85	4.18	86.19	3.08	63.51	2.75	56.70
Hemicelluloses.....	58.42	43.34	74.19	35.87	61.40	27.51	47.09
Celluloses.....	106.66	74.21	69.58	52.73	49.44	39.76	37.28
Lignins.....	40.51	40.00	98.74	31.08	76.72	28.20	69.61
Crude protein.....	2.25	4.97	220.88	4.05	180.00	5.40	240.00

per cent respectively. In other words, these two groups of carbohydrates, which make up 60 per cent of the total constituents of the straw, diminished to a considerably greater extent than did the total organic matter. This reduction was balanced by the greater resistance of the lignins to decomposition and by the building up of protein material, a phenomenon already observed as a result of decomposition of the corn stalks.

Because of the comparatively greater abundance of available carbohydrates (celluloses and hemicelluloses), the microorganisms have brought about in the case of the rye straw even a greater proportional increase in the protein content than that which resulted from the decomposition of the corn stalks. This increase was naturally more marked in the presence of additional available nitrogen. The actual increase in the protein content of the residual material was 100 and 140 per cent, without and with the addition of nitrogen, respectively. The increase in the protein content of the decomposing straw

without additional inorganic nitrogen is found to be largely at the expense of the water-soluble nitrogen compounds, which were thereby made water-insoluble. This is brought out in table 11. With the progress of decomposition, there was a gradual decrease of the nitrogen soluble in cold water and a corresponding increase in the nitrogen hydrolyzable by dilute hydrochloric acid and in the more resistant or so-called "humin" nitrogen, pointing to the building up by microorganisms of proteins and other complex organic nitrogenous compounds. Practically all the nitrogen was recovered in the residual

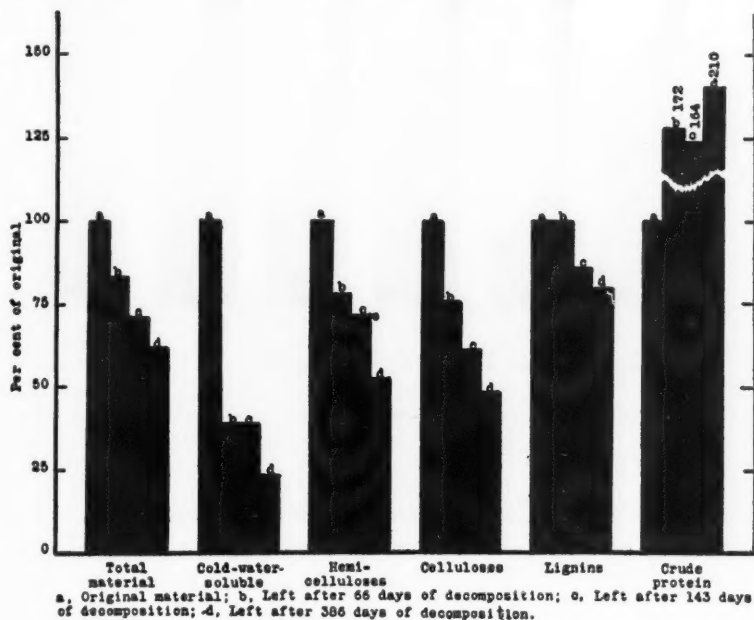


FIG. 3. DECOMPOSITION OF VARIOUS CHEMICAL CONSTITUENTS OF RYE STRAW WITHOUT ADDITIONAL NUTRIENT SALTS

material, pointing to three interesting considerations: (a) there is no loss in nitrogen, either by volatilization or reduction processes, as long as there is sufficient available energy for the activities of microorganisms; (b) there is no gain in nitrogen, through processes of non-symbiotic fixation, when only celluloses and hemicelluloses are available as sources of energy even in the presence of numerous cellulose-decomposing organisms; (c) at least some of the nitrogenous compounds synthesized by the microorganisms are only slowly available sources of nitrogen for soil microorganisms, otherwise the celluloses and hemicelluloses would have undergone a much more rapid decomposition.

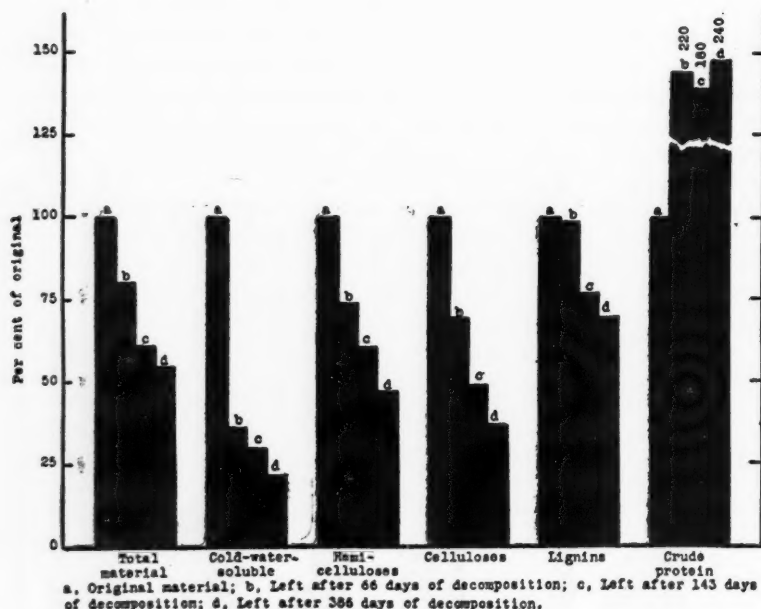


FIG. 4. DECOMPOSITION OF VARIOUS CHEMICAL CONSTITUENTS OF RYE STRAW WITH ADDITIONAL NUTRIENT SALTS

TABLE 11

*Nitrogen transformation in the decomposition of rye straw*  
In per cent of total material

FORM OF NITROGEN	NO ADDITIONAL NITROGEN				AMMONIUM PHOSPHATE ADDED			
	Incubation				Incubation			
	0 days	66 days	143 days	386 days	0 days	66 days	143 days	386 days
Total nitrogen.....	0.24	0.33	0.39	0.50	0.31	0.42	0.47	0.64
Soluble in cold water.....	0.11	0.03	0.05	0.02	0.18	0.03	0.05	0.02
Soluble in hot water.....	0	0.03	0.04	0.04	0	0.03	0.05	0.05
Hydrolyzable by 2 per cent HCl.....	0.04	0.08	0.10	....	0.04	0.12	0.14	....
"Humin" nitrogen, not acted upon by autoclaving with hot 6 per cent H <sub>2</sub> SO <sub>4</sub> ..	0.06	0.10	0.13	....	0.06	0.10	0.14	....

#### DECOMPOSITION OF OAK LEAVES

The mature oak leaves were distinctly different in chemical composition from the corn stalks and the rye straw. The leaves were characterized by a high content of fats and waxes (ether-soluble fraction), a very high lignin (and

cutin) content, and were rich in materials soluble in hot water (tannins). On the other hand, the celluloses and hemicelluloses were not very abundant in the leaves. Their nitrogen content was higher than that of either the corn stalks or the straw. One would expect, therefore, that the leaves should show a decided difference in the nature and rapidity of decomposition from that of the two plant materials previously reported.

TABLE 12

*Chemical composition of mature oak leaves at different stages of decomposition, without the addition of nutrient salts*

On per cent basis of dry material

CHEMICAL CONSTITUENTS	ORIGINAL PLANT MATERIAL	AFTER DAYS OF DECOMPOSITION		
		66	143	386
Ether-soluble.....	3.71	3.53	2.82	1.77
Cold-water-soluble.....	8.28	2.02	1.15	1.69
Hot-water-soluble.....	5.65	3.91	2.15	2.16
Hemicelluloses.....	12.93	12.10	13.03	12.27
Celluloses.....	13.78	11.78	10.41	8.92
Lignins.....	30.30	40.02	42.65	44.50
Crude protein.....	4.25	6.00	6.13	7.44
Ash.....	5.09	6.50	6.90	8.12

TABLE 13

*Chemical composition of mature oak leaves at different stages of decomposition, with the addition of nutrient salts*

On per cent basis of dry material

CHEMICAL CONSTITUENTS	ORIGINAL PLANT MATERIAL	AFTER DAYS OF DECOMPOSITION		
		66	143	386
Ether-soluble.....	3.71	2.65	1.74	0.67
Cold-water-soluble.....	8.28	1.60	1.44	2.86
Hot-water-soluble.....	5.65	3.10	2.04	2.44
Hemicelluloses.....	12.93	12.59	13.27	13.25
Celluloses.....	13.78	11.90	10.94	9.23
Lignins.....	30.30	40.40	40.55	40.35
Crude protein.....	4.25	6.62	6.88	8.25
Ash.....	5.09	8.00	9.00	10.33

The chemical composition of the oak leaves at different stages of decomposition is given in tables 12 and 13, and the actual concentration of the different organic chemical complexes which have undergone decomposition is recorded in tables 14 and 15 and figures 5 and 6. In the case of this plant material as well, half of the pots received inorganic salts including nitrogen and half did not. The composts of oak leaves were allowed to incubate under the same conditions as the other two plant materials and analyzed after 66, 143, and 386 days.



The results show that although the leaves contained more nitrogen (0.77 per cent) than did the corn stalks, their decomposition was considerably slower. It was similar to that of the rye straw, which contained only about one-third or less of the nitrogen content of the leaves. These differences in the rate

TABLE 14

*Total decomposition of the various organic constituents in mature oak leaves, without the addition of nutrient salts*

ORGANIC CONSTITUENTS	ORIGINAL MATERIAL	ORGANIC SUBSTANCES LEFT, AFTER DAYS OF DECOMPOSITION					
		66		143		386	
		Total residue	Per cent of original	Total residue	Per cent of original	Total residue	Per cent of original
	gm.	gm.		gm.		gm.	
Total dry material.....	223.00	173.00	77.58	158.00	70.85	129.00	57.85
Ether-soluble fraction.....	8.27	6.11	73.88	4.46	53.93	2.28	27.57
Cold-water-soluble organic matter....	18.46	3.49	18.91	1.82	9.86	2.18	11.81
Hot-water-soluble organic matter....	12.60	6.76	53.66	3.40	26.98	2.79	22.14
Hemicelluloses.....	28.83	20.93	72.54	20.59	71.39	15.83	54.91
Celluloses.....	30.73	20.37	66.34	16.45	53.54	11.51	37.44
Lignins.....	67.56	69.23	102.47	67.39	99.75	57.41	84.97
Crude protein.....	4.25	10.38	244.24	9.69	228.00	9.60	225.88

TABLE 15

*Total decomposition of the various organic constituents in mature oak leaves, in the presence of added nutrient salts*

ORGANIC CONSTITUENTS	ORIGINAL MATERIAL	ORGANIC SUBSTANCES LEFT, AFTER DAYS OF DECOMPOSITION					
		66		143		386	
		Total residue	Per cent of original	Total residue	Per cent of original	Total residue	Per cent of original
	gm.	gm.		gm.		gm.	
Total dry material.....	223.00	171.00	76.68	157.00	70.40	125.00	56.05
Ether-soluble fraction.....	8.27	4.53	54.78	2.73	33.01	0.84	10.16
Cold-water-soluble organic matter....	18.46	2.74	14.84	2.26	12.24	3.58	19.39
Hot-water-soluble organic matter....	12.60	5.30	42.06	3.20	25.40	3.05	24.21
Hemicelluloses.....	28.83	21.53	74.63	20.83	72.20	16.56	57.44
Celluloses.....	30.73	20.34	66.23	17.18	55.91	11.54	37.55
Lignins.....	67.56	68.48	101.36	63.66	94.23	50.44	74.66
Crude protein.....	4.25	11.32	266.35	10.80	254.12	10.31	242.59

and degree of decomposition of the three plant materials lead us to the conclusion that the abundance of nitrogen in the plant residue undergoing decomposition is not the only controlling factor in the rapidity with which microorganisms are capable of attacking it. Actually, the addition of avail-

able nitrogen had no appreciable influence in hastening the decomposition of the leaves, as seen by the reduction in the total organic matter, as well as the celluloses and hemicelluloses.

It has been found, in experiments reported previously (15), that the addition of a small amount of available nitrogen had a decidedly favorable effect upon the decomposition of mature oak leaves, as measured by the evolution of carbon dioxide, the absorption of available nitrogen, and the decomposition of total organic matter, celluloses, and hemicelluloses. The fact, however,

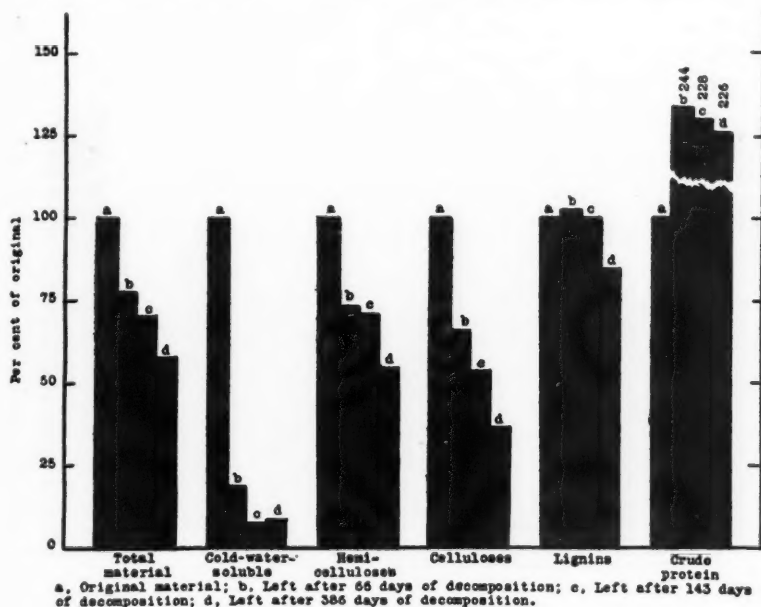


FIG. 5. DECOMPOSITION OF VARIOUS CHEMICAL CONSTITUENTS OF OAK LEAVES WITHOUT ADDITIONAL NUTRIENT SALTS

that in these experiments no such striking differences have been found, do not indicate a possible discrepancy between these two sets of data. The difference is due entirely to the fact that in the previous investigations only a short period of incubation (28 days) was employed; in these studies, however, the first analysis was made only after 68 days of incubation. In other words, even in the case of a plant material with 0.77 per cent nitrogen, the addition of a small amount of available nitrogen will exert a stimulating effect upon its decomposition during the early stages. However, when decomposition has advanced, there will be sufficient nitrogen liberated from the degradation of the plant proteins to take care of the celluloses and hemicelluloses. This

is true especially in the case of a material like oak leaves, the decomposition of which, due to the high lignin, tannin, and wax contents, is considerably delayed, when compared with that of straw and corn stalks. Even in the early periods of incubation, the effect of additional nitrogen upon the decomposition of the oak leaves was considerably less than upon the decomposition of rye straw and corn stalks, as shown in the earlier contribution (15).

Although the water-soluble substances of the oak leaves decomposed very rapidly, the celluloses and hemicelluloses resisted decomposition more than

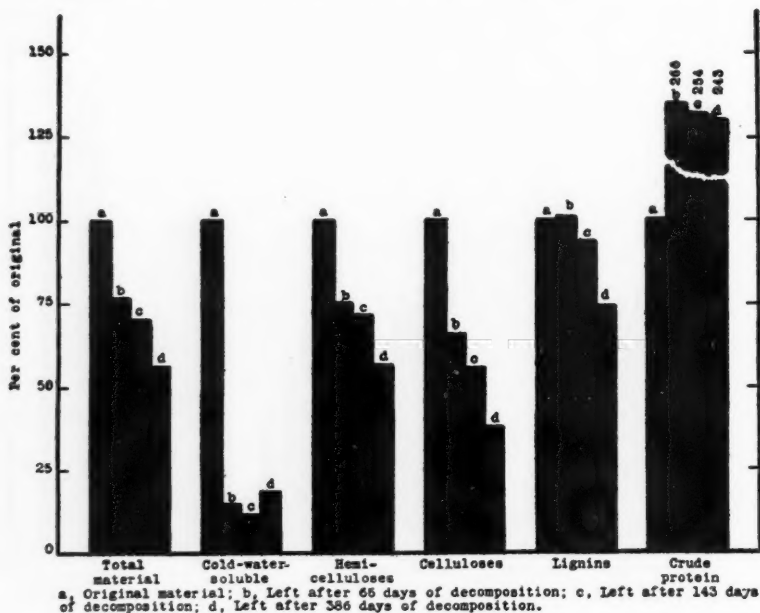


FIG. 6. DECOMPOSITION OF VARIOUS CHEMICAL CONSTITUENTS OF OAK LEAVES WITH ADDITIONAL NUTRIENT SALTS

in the case of the two other plant materials. This is due, not to the lack of the available nitrogen, as found in the case of the rye straw, but to the abundance of the lignins. It has been shown elsewhere (13) that the lignins are not only resistant to decomposition, but they even delay the disintegration of the celluloses. The removal of the lignins from a plant residue hastens the decomposition of the celluloses. In the case of the oak leaves, the lignins remained practically undecomposed, until a year had passed, and only then a small fraction had disappeared, the nature of the change still remaining undetermined.

The crude or water-insoluble proteins have also increased in the case of the

oak leaves. Where nitrogen was added in the form of ammonia, it was changed rapidly into organic nitrogen by the synthetic action of the microorganisms. When no inorganic nitrogen was added, the water-soluble nitrogen compounds disappeared, giving rise to water-insoluble nitrogenous complexes. This is brought out in table 16.

When the results of the decomposition of mature oak leaves are compared with that of green oak leaves, as reported elsewhere (16), marked differences are observed, due entirely to differences in the chemical composition of the two kinds of leaves used in both experiments. The younger leaves were richer in water-soluble constituents and in nitrogen, and poorer in lignins. As a result of these differences, the younger leaves decomposed much more rapidly, large amounts of nitrogen actually becoming liberated in the form

TABLE 16  
*Nitrogen transformation in the decomposition of oak leaves*  
In per cent of total material

FORM OF NITROGEN	NO ADDITIONAL NITROGEN				AMMONIUM PHOSPHATE ADDED			
	Incubation				Incubation			
	0 days	66 days	143 days	386 days	0 days	66 days	143 days	386 days
Total nitrogen . . . . .	0.77	1.03	1.06	1.26	0.87	1.15	1.20	1.43
Soluble in cold water . . . . .	0.09	0.02	0.04	0.03	0.19	0.04	0.05	0.04
Soluble in hot water . . . . .	Trace	0.05	0.04	0.05	Trace	0.05	0.05	0.07
Hydrolizable by 2 per cent HCl . . . .	0.18	0.17	0.22	....	0.18	0.21	0.27	....
"Humin" nitrogen, not acted upon by autoclaving with 6 per cent H <sub>2</sub> SO <sub>4</sub> . . . . .	0.30	0.47	0.53	0.49	0.30	0.49	0.53	0.53

of ammonia even within a period of six months of decomposition under aerobic conditions.

#### DECOMPOSITION OF ALFALFA

The chemical composition of the alfalfa plant used in these experiments differed considerably from that of the other three plant materials. As a representative of the group of leguminous plants, it was characterized by a high nitrogen content, a large part of which was water-soluble. It contained also the largest amount of cold-water-soluble substances, which is the fraction previously found to disappear most rapidly when a plant is undergoing decomposition. The alfalfa also contained the lowest lignin content; this would tend to favor further the ease of its decomposition. One would expect from an analysis of the chemical composition of this material that it should undergo rapid disintegration, especially during the early stages.

It has been shown previously (15), that when a plant material contains about 1.7 per cent nitrogen it undergoes rapid decomposition even when no

additional nitrogen is available. In view of the fact that the alfalfa contained more than this amount of nitrogen, the addition of inorganic nitrogen should not exert any favorable effect upon the rapidity of its decomposition. This was actually found to be the case. The decomposing alfalfa receiving ammonium phosphate and calcium carbonate actually decomposed more

TABLE 17  
*Chemical composition of alfalfa at different stages of decomposition, without the addition of nutrient salts*  
On per cent basis of dry material

CHEMICAL CONSTITUENTS	ORIGINAL PLANT MATERIAL	AFTER DAYS OF DECOMPOSITION			
		27	68	205	405
Ether-soluble.....	2.75	.....	1.90	0.71	0.90
Cold-water-soluble.....	12.44	12.55	11.08	9.16	11.15
Hot-water-soluble.....	4.80	5.13	7.13	6.50	6.34
Hemicelluloses.....	8.52	6.24	6.39	7.29	8.22
Celluloses.....	26.71	22.63	16.48	15.15	15.90
Lignins.....	10.78	15.12	14.85	18.37	16.08
Crude protein.....	8.13	8.43	7.31	10.31	9.18
Ash.....	10.30	.....	.....	23.43	24.88

TABLE 18  
*Chemical composition of alfalfa at different stages of decomposition, with the addition of nutrient salts*  
On per cent basis of dry material

CHEMICAL CONSTITUENTS	ORIGINAL PLANT MATERIAL	AFTER DAYS OF DECOMPOSITION			
		27	68	205	405
Ether-soluble.....	2.75	.....	2.02	1.08	0.60
Cold-water-soluble.....	12.44	10.10	10.87	8.23	9.81
Hot-water-soluble.....	4.80	4.34	5.56	5.94	6.69
Hemicelluloses.....	8.52	6.15	6.19	8.07	7.16
Celluloses.....	26.71	26.00	19.31	17.22	17.55
Lignins.....	10.78	14.91	16.51	16.98	15.62
Crude protein.....	8.13	7.94	8.50	12.25	8.56
Ash.....	10.30	.....	.....	25.54	27.88

slowly than the material not receiving any additional salts. This can be explained as follows: the rapid decomposition of the alfalfa, rich in soluble nitrogen, led to an abundant liberation of ammonia. Because the compost was enclosed in a covered pot, the reaction became alkaline. The addition of ammonium phosphate and calcium carbonate tended to make the reaction even more alkaline, so that the ammonia actually saturated the atmosphere of the compost; this resulted in a considerable depression of many groups of organisms, notably of the fungi and various bacteria. This depression had a

TABLE 19

*Total decomposition of the various organic constituents of alfalfa, without the addition of nutrient salts*

ORGANIC CONSTITUENTS	ORIGINAL MATERIAL	ORGANIC SUBSTANCES LEFT, AFTER DAYS OF DECOMPOSITION							
		27		68		205		405	
		Total residue	Per cent of original	Total residue	Per cent of original	Total residue	Per cent of original	Total residue	Per cent of original
	gm.	gm.		gm.		gm.		gm.	
Total dry material . . . . .	260.00	181.00	70.00	151.80	58.40	119.10	45.80	100.00	38.50
Ether-soluble fraction . . . .	7.15	.....	.....	2.88	40.28	0.85	11.89	0.90	12.59
Cold-water-soluble organic matter . . . . .	32.34	22.72	70.25	16.82	52.01	10.91	33.74	11.15	34.48
Hot-water-soluble organic matter . . . . .	12.48	9.29	74.44	10.82	86.70	7.74	62.02	6.34	50.80
Hemicelluloses . . . . .	22.16	11.29	50.94	9.70	43.77	8.68	39.17	8.22	37.09
Celluloses . . . . .	69.45	40.95	58.96	25.02	36.03	18.04	25.98	15.90	22.89
Lignins . . . . .	28.02	27.37	97.68	22.54	80.44	21.88	78.09	16.08	57.39
Crude protein . . . . .	21.14	15.27	72.23	11.10	52.51	12.28	58.09	9.18	43.42

TABLE 20

*Total decomposition of the various organic constituents of alfalfa, with the addition of nutrient salts*

ORGANIC CONSTITUENTS	ORIGINAL MATERIAL	ORGANIC SUBSTANCES LEFT, AFTER DAYS OF INCUBATION							
		27		68		205		405	
		Total residue	Per cent of original	Total residue	Per cent of original	Total residue	Per cent of original	Total residue	Per cent of original
	gm.	gm.		gm.		gm.		gm.	
Total dry material . . . . .	260.00	207.00	79.62	151.89	58.40	116.00	44.50	109.80	42.20
Ether-soluble fraction . . . .	7.15	.....	.....	3.07	42.94	1.25	17.48	0.66	9.23
Cold-water-soluble organic matter . . . . .	32.34	20.71	64.04	16.51	51.05	9.55	29.53	10.77	33.30
Hot-water-soluble organic matter . . . . .	12.48	8.90	71.31	8.44	67.63	6.89	55.21	7.35	58.89
Hemicelluloses . . . . .	22.16	12.60	56.86	9.40	42.42	9.36	42.24	7.86	35.47
Celluloses . . . . .	69.45	53.30	76.75	29.32	42.22	19.98	28.77	19.27	27.75
Lignins . . . . .	28.02	.....	.....	25.07	89.47	19.70	70.31	17.15	61.21
Crude protein . . . . .	21.14	16.28	77.01	12.91	61.07	14.21	67.22	9.40	44.47

marked effect upon the rapidity of decomposition of some of the organic complexes in the alfalfa, especially of the celluloses.

Tables 17 and 18 give the chemical composition of the alfalfa at the different stages of decomposition. Analyses were made after 27, 68, 205, and 405 days of incubation at 25–27°C. Tables 19 and 20 and figures 7 and 8 give the total amounts of the various chemical constituents in the residual matter, at the different periods of incubation.

A comparison of the rapidity of decomposition of corn stalks, rye straw, and alfalfa, as measured by the evolution of carbon dioxide, has shown (15)

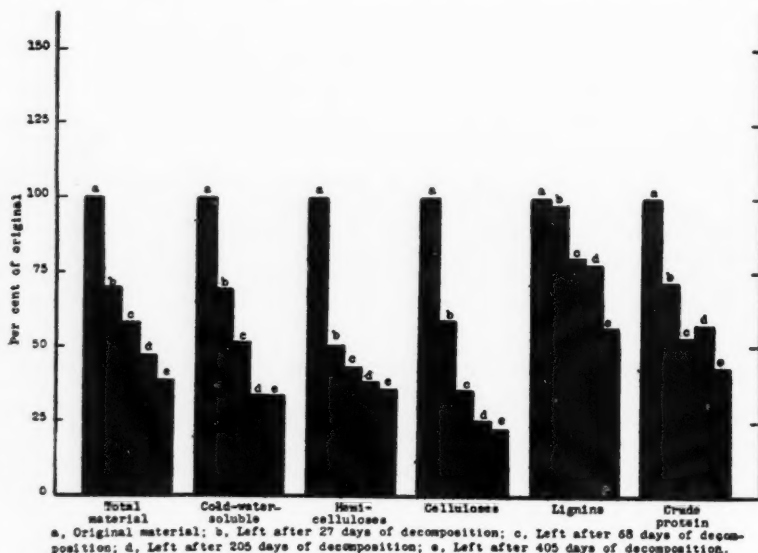


FIG. 7. DECOMPOSITION OF VARIOUS CHEMICAL CONSTITUENTS OF ALFALFA WITHOUT ADDITIONAL NUTRIENT SALTS

that the alfalfa decomposed far more rapidly than did the other two materials. However, when a long period of incubation is used, the alfalfa is found to leave a considerably larger amount of residual material than do the corn stalks. This is due primarily to the artificial conditions under which these studies were carried out. The rapid accumulation of ammonia as a result of the protein decomposition in the nitrogen-rich alfalfa prevented a rapid development of the fungi and various bacteria, which accounts for the larger amount of celluloses and hemicelluloses that remained undecomposed than in the case of the corn stalks.

The lignins of the alfalfa were also more resistant to decomposition than the other organic complexes. Although the relative protein content of the



compost tended to increase with the advance of decomposition, especially within the first 205 days, the total protein content diminished rapidly. This

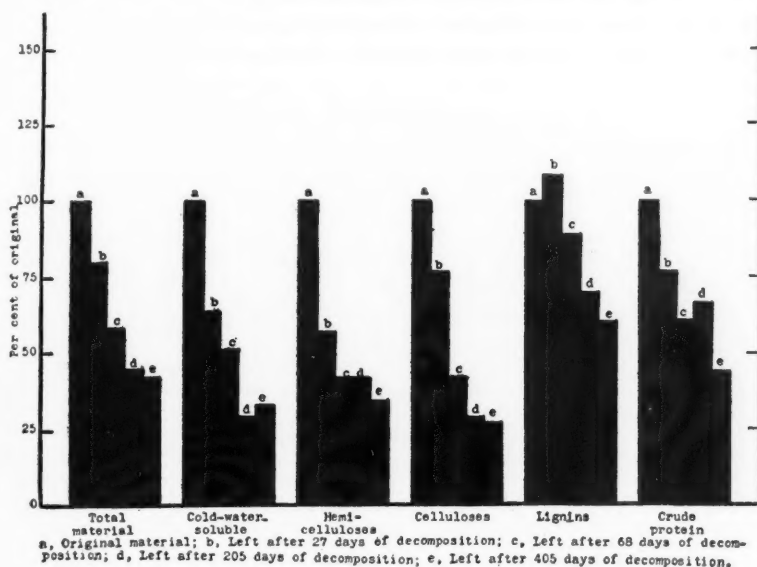


FIG. 8. DECOMPOSITION OF VARIOUS CHEMICAL CONSTITUENTS OF ALFALFA WITH ADDITIONAL NUTRIENT SALTS

TABLE 21

*Nitrogen transformation in the aerobic decomposition of alfalfa*

In per cent of total material

FORM OF NITROGEN	NO ADDITIONAL NITROGEN					AMMONIUM PHOSPHATE ADDED				
	Incubation					Incubation				
	0 days	27 days	68 days	205 days	405 days	0 days	27 days	68 days	205 days	405 days
Total nitrogen.....	2.58	2.63	2.70	2.60	2.40	2.66	2.32	2.47	2.80	2.32
Ammonia nitrogen.....	0	0.39	1.66	....	....	0.08	0.51	1.68	....	....
Soluble in cold water.....	0.93	0.98	0.78	0.57	0.61	1.01	0.79	0.75	0.59	0.65
Soluble in hot water.....	0.35	0.30	0.39	0.38	0.32	0.35	0.26	0.36	0.35	0.30
Hydrolizable in 2 per cent HCl.....	0.59	0.38	0.47	....	0.62	0.59	0.37	0.51	....	0.57
"Humin" nitrogen, not acted upon by autoclaving with 6 per cent H <sub>2</sub> SO <sub>4</sub> ....	0.37	0.45	0.41	0.39	0.34	0.37	0.42	0.49	0.47	0.38

is the opposite of what has taken place in the case of the other three plant materials and is due to the initial high protein content of the alfalfa. This is brought out in table 21. The total nitrogen remained at about the same

level, whereas the water-soluble nitrogen disappeared only partly. There was also no marked accumulation of proteins readily hydrolyzable by dilute (2 per cent) hydrochloric acid and of the non-hydrolyzable, so-called "humin" nitrogen. These facts are again distinctly different from those which have been found in the case of the nitrogen-poor plant materials.

#### DISCUSSION

An analysis of the data dealing with the decomposition of four different plant materials, varying markedly in origin and in chemical composition, brings out some illuminating facts. These can be summarized as follows: *the rapidity and nature of decomposition of plant residues under aerobic conditions depend primarily upon the chemical composition of the particular plant materials.*

Among the various chemical constituents of the plant materials which may influence their decomposition, the following deserve careful consideration:

1. The amount and nature of the constituents which are soluble in cold water.
2. The abundance of the celluloses and hemicelluloses.
3. The amount and nature of the nitrogenous complexes.
4. The abundance of the lignins.

The greater the amount of water-soluble material in a plant residue the more rapid will be its decomposition, especially during the early stages. This is easy to understand, since the water-soluble fraction comprises the simple sugars, amino acids, soluble salts,—substances all readily used by a great number of microorganisms, both fungi (especially the Phycomycetes) and bacteria (especially the spore-forming organisms). The younger a plant is, the higher is its content of water-soluble substances. The decrease in the rapidity of decomposition with the increase in age of plant is due, among other factors, to a decrease in this group of plant constituents. Further, the decomposition of sugars, organic acids, and other water-soluble organic complexes can be carried on in the soil by both aerobic and anaerobic bacteria, which are capable of using gaseous atmospheric nitrogen; hence, the amount and availability of the nitrogen are not controlling factors in the decomposition of these organic materials.

The most abundant groups of constituents in the various plant residues which undergo decomposition in the soil or in manure are the celluloses and hemicelluloses. Usually they make up about 50 to 65 per cent of the sum total of the dry plant material. Their decomposition is carried out by certain groups of fungi and specific bacteria. These organisms synthesize considerable cell substance in the process of decomposition of the celluloses. For this purpose a certain amount of available nitrogen is required. Hence the decomposition of the celluloses and hemicelluloses depends upon the presence of organisms capable of decomposing them and upon the amount of available nitrogen.

The celluloses are usually not present in the plant residues in a free condition but are combined largely with lignins, in the form of ligno-celluloses. Whether the combination is chemical or physical in nature, the presence of lignin markedly influences the ability of the microorganisms to decompose the celluloses. The various chemical treatments which have in view an increase of digestibility by animals of plant residues high in lignins consist in the partial dissolution of the lignins. The lignins themselves are decomposed by microorganisms (with certain few exceptions, as in the case of some wood-destroying *Hymenomycetes*) only to a very limited extent, even under aerobic conditions. A long time may elapse before any measurable reduction in the lignins will be observed.

It must be kept in mind that the decomposition processes taking place in these studies were carried out at an optimum temperature and moisture; the conditions were also favorable for the activities of aerobic organisms. But even under these conditions, the decomposition of the lignins has been very limited in comparison with that of the celluloses and other organic complexes. In the case of the corn stalks with nutrients, there was left, after 405 days of decomposition, 20.30 per cent of the total organic matter, 3.83 per cent of the cellulose, and 42.49 per cent of the lignin. In the case of the rye straw, there was left, after 386 days incubation, 55.23 per cent of the total organic matter, 37.28 per cent of the cellulose, and 69.61 per cent of the lignin. In the case of the oak leaves, there was left, after 386 days decomposition, 56.05 per cent of the total organic matter, 37.55 per cent of the cellulose, and 74.66 per cent of the lignin. In the case of the alfalfa, there was left, after 405 days of decomposition, 42.20 per cent of the total organic matter, 27.75 per cent of the cellulose, and 61.21 per cent of the lignin. In other words, all the four plant materials, obtained from different sources and varying markedly in chemical composition, behaved alike as far as the lignins were concerned. The reduction of the lignins was considerably less than that of the total plant residues and much less than any of the other organic plant constituents.

The behavior of the nitrogen complexes deserves also special consideration. The rapid increase in the protein content as a result of the decomposition of plant residues with a low nitrogen content has been definitely established. That this protein is a result of the synthesizing activities of the microorganisms and that a definite ratio exists between the amount of cellulose decomposed and the nitrogen transformed from an inorganic into an organic form has been amply demonstrated previously. On the other hand, the results on the decomposition of alfalfa, a plant residue with a nitrogen content greater than 1.7 per cent, showed a decrease of the total protein, although accompanied at the same time by an increase in the relative nitrogen content of the decomposing material. In other words, even in the case of a protein-rich plant material, the processes of decomposition were accompanied by synthesis of new proteins, so that the nitrogenous complexes which resulted

from the decomposition of the alfalfa are of an entirely different nature from the original plant proteins.

Among the other organic constituents of the plant residues undergoing decomposition, the hot-water-soluble fraction deserves some consideration. This fraction has decreased to a less extent than many of the other groups of plant complexes. It is quite distinct from the cold-water-soluble fraction in that it is reduced much less rapidly than the latter. This is due to two factors: (a) Hot water extracts certain complexes, like the tannins, which are quite resistant to decomposition; (b) the microorganisms synthesize various substances soluble in hot water but not in cold water.

The ether-soluble fraction comprises also a heterogeneous group of complexes, including various oils, fats, waxes, and sterols. Some of these decompose quite rapidly, whereas others are very resistant to decomposition. This is largely the reason why the ether-soluble fraction of alfalfa or corn stalks decomposed readily whereas that of the straw proved to be much more resistant to decomposition.

#### SUMMARY

1. The decomposition of four plant materials; namely, corn stalks, rye straw, oak leaves, and alfalfa plants, has been studied under aerobic conditions, in the presence of an optimum amount of moisture and at 25–27°C.

2. The processes of decomposition have been followed by determining the disappearance of the total organic matter as well as of the more important groups of organic complexes.

3. The nature and rapidity of decomposition of different plant materials are markedly influenced by their chemical composition, provided the conditions for decomposition are the same.

4. The decomposition of the sugars, celluloses, hemicelluloses, fats, and proteins account for most of the decomposed plant materials.

5. The lignins are more resistant to decomposition and tend, therefore, to accumulate. Under aerobic conditions, however, there is a decided reduction in the total lignin content, indicating that, although it is attacked less readily than the celluloses and proteins, its resistance to decomposition is only relative.

6. In the case of plant materials with a low nitrogen content (0.2 to 1.7 per cent), the decomposition of the organic matter is accompanied by a relative and absolute increase in the crude protein content. This is due to the synthesizing activities of the microorganisms, which obtain their energy from the decomposition of the celluloses and hemicelluloses.

7. The celluloses and hemicelluloses, including the pentosans, disappear more rapidly than can be accounted for by the reduction in total organic matter. This is balanced by the accumulation of the lignins and proteins.

8. Among the other synthesized products, the hemicelluloses occupy a prominent place. This is partly accounted for by the fact that, although the pentosans comprising most of the hemicelluloses in the plant material begin

to decompose more rapidly than the celluloses, toward the end of decomposition there is left more hemicellulose than cellulose.

9. The addition of available inorganic nitrogen salt hastens the decomposition of celluloses and hemicelluloses, hence of those plant materials which are rich in celluloses and hemicelluloses and poor in proteins.

10. The residues left, after the plant materials have decomposed for a period of 12 to 14 months at an optimum temperature and moisture and under aerobic conditions, possess all the properties of soil organic matter or soil "humus." This is true especially of the corn stalks which have undergone most rapid decomposition.

11. This residual organic matter or "humus" is made up chiefly of lignins or modified lignin complexes largely of plant origin, of proteins and other complex organic nitrogenous compounds largely of microbial origin, of hemicelluloses partly of plant and partly of microbial origin, of a small amount of celluloses undergoing decomposition, and of varying concentrations of a number of different other organic complexes either in the process of decomposition, resistant to decomposition, or products of decomposition.

12. This residual material or "humus" is not in a state of equilibrium but undergoes continuous change, the rate of change becoming constantly slower, approaching that of the soil "humus."

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